Running title: Syn-rift alluvial systems record. Upper Jurassic of the NW Iberian Basin

EARLY SYN-RIFT EVOLUTION IN THE W CAMEROS BASIN (UPPER JURASSIC, NW IBERIAN RANGE) SPAIN.

Sacristán-Horcajada, Sara[a,b], Mas, Ramón[a,b], Arribas, Mª Eugenia[c,†]

[a] Departamento de Estratigrafía, Universidad Complutense de Madrid, C/ José Antonio Nováis 12, 28040 Madrid, Spain.

[b] Instituto de Geociencias IGEO (CSIC, UCM), C/ José Antonio Novais 12, 28040 Madrid, Spain.

[c]Departamento de Petrología y Geoquímica, Universidad Complutense de Madrid, C/ José Antonio Nováis 12, 28040 Madrid, Spain.

† Corresponding Author: Tel.: +34913944918. Fax: +34915442535. Email: earribas@geo.ucm.es

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ABSTRACT

Alluvial systems are sensitive sedimentary systems that can preserve useful information about tectonic, drainage area (lithology and size) and climate. However, research on this subject over the last three decades has made it evident that the interaction of these three factors and their control over the alluvial architecture and facies are complex. The stratigraphic and sedimentological analysis of the earliest syn-rift sedimentary record (Tithonian) in the W Cameros Basin has confirmed that sedimentation during the beginning of extension in this area took place in a series of halfgraben basins in which three different types of fan-shaped alluvial systems were deposited: two relatively large systems, specifically, a “highly channelized alluvial fan system” and a “fluvial distributary fan system changing downstream to an axial tributary fluvial system”, were the exception; and small “poorly channelized alluvial fan systems” were the norm. A semiarid climate is inferred during this earliest syn-rift sedimentary record from the steady and extensive calcrete development. This semiarid climate should play an important role both in how coarser sediment discharges to the rift halfgraben basins occurred and in the dominant transverse organization of the alluvial depositional systems. However, the climate and source-area lithology can be considered steady factors, so the main factors considered as the cause of these sedimentary and architectural heterogeneities are the tectonics and drainage-area sizes, and specifically, the different behavior of each extensional structure in terms of the rate of tectonic uplift and subsidence. This indicates how fault activity and drainage-area sizes during the earliest stages of a rift system can generate high degrees of

heterogeneity in the architecture of alluvial basins and how this heterogeneity is recorded by the alluvial systems in the form of differences in their facies association and architecture. Therefore, this work concludes that both tectonics and catchment sizes exerted primary control on the sedimentary characteristics of associated alluvial systems in basins generated from this type of extensional setting, and care must be taken when making climatic and tectonic interpretations using the sedimentary record of these alluvial systems because many changes that traditionally have been attributed to climate variability can be explained solely by the differential behavior of each extensional structure and/or changes in its associated drainage area.

KEYWORDS: tectonic and catchment controls, halfgraben basins, rift system, alluvial systems and architecture, NW Iberian Range.

INTRODUCTION AND AIMS

Understanding the evolution of sedimentary architecture in ancient extensional settings is important because they are a record of past rift processes during cycles of plate break-up, they preserve important information about climate changes or faunal evolution, and they contain potential economic reserves of hydrocarbons, water, and minerals. Special attention has been paid to the earliest stages of rift development or rift initiation stage (*sensu* Cowie et al. 2000, Gawthorpe and Leeder 2000), during which sedimentation takes place in a set of individual extensional faults linked by transfer zones whose activity and interaction control the stratigraphic architecture of the extensional basins (Leeder 1999, Cowie et al. 2000, Davies et al. 2000, Gawthorpe and Leeder 2000). Fault activity can vary considerably in space and time during the first stages of extension, even along the same fault zone, generating several isolated and small depocenters which can display different sedimentary architectures (Cowie et al. 2000).

The most common depositional systems that developed during these earliest rift stages are alluvial fan systems associated with distal fluvial or lacustrine systems (Miall 1981, Leeder and Gawthorpe 1987, Gawthorpe and Leeder 2000). Alluvial systems (alluvial fans and fluvial systems) have attracted great attention in the geological literature (see collections like those edited or written by Miall 1981, Nilsen 1982, Rachocki and Church 1990, Schumm et al. 2000, Harvey et al. 2005, and Miall 2014) because they are sensitive sedimentary systems which can preserve useful information about evolution of tectonics and climate, and therefore they have been used as tools to unravel the influence and interaction of these two factors on the evolution of ancient extensional basins. Alluvial-fan morphology is directly related to sediment supply and drainage patterns (Harvey et al. 2005), and thus, any change in these two factors, due either to climate or to tectonics, will led to changes in the alluvial architecture. Although climate change seems to be an important controlling factor (Harvey 1990, Lecce 1990, Maizels 1990, Blair and McPherson 1994b, Harvey et al. 2005), many works have demonstrated the great influence of tectonics (Miall 1981, Nilsen 1982, Lecce 1990, Blair and McPherson 1994b) and drainage area lithology (Denny 1967, Hooke 1967, Bull 1972, Blair and McPherson 1994a) on the evolution of alluvial systems, especially in some specific tectonic settings. Taking into account these complex interactions, it is clear that alluvial systems are a continuum of depositional processes (Harvey et al. 2005), ranging from small debris cones to large fluvially dominated megafans, and that the initial classification of dry or wet alluvial systems (Schumm 1977) was an oversimplification (Blair and McPherson 1994a and 1994b, Harvey et al. 2005) which can led to misinterpretations of the sedimentary record.

This work aims to contribute to the knowledge about how the sedimentary record of alluvial systems can be used as a tool to assess tectonic evolution in sedimentary basins by analyzing the earliest syn-rift sedimentary record (Tithonian) of the Cameros Basin (N Spain). This area is chosen for the examination of ancient alluvial systems because it includes different halfgraben basins characterized by different alluvial architectures, which developed contemporaneously in the same paleogeographic area and in relation to the same rift process (Sacristán-Horcajada et al. 2012c, Sacristán-Horcajada et al. 2013). Thus, climate is considered as a steady factor, leaving tectonics and drainage-area size and lithology as the main controlling factors to consider. The main objective of this work is to analyze the sedimentological, architectural, and paleogeographical differences of these alluvial basins and relate them with the main factors controlling them to improve the knowledge about the complexity of the earliest continental sedimentary record in extensional basins and constrain the use of alluvial systems as tools to unravel this complexity.

GEOLOGICAL SETTING

The Cameros Basin

The Cameros Basin, located in the northern sector of the Iberian Range (Fig. 1A), is the northwestern most basin that formed as part of the Mesozoic Iberian Rift System (Mas et al. 1993, Guimerà et al. 1995, Salas et al. 2001, Mas et al., 2002). This rift system was divided into four major cycles or megasequences (Salas et al. 2001, Mas et al., 2002, 2003, 2011), two corresponding to rift deposits (extensional phases represented by Megasequences 1 and 3) and two corresponding to post-rift deposits (post-extensional predominating thermal phases represented by Megasequences 2 and 4). The sedimentary record of the Cameros Basin represents the third of these megasequences, which was unconformably deposited from the Early Tithonian to the Early Albian over the Middle to Upper Jurassic marine platforms (Figs. 1B, 2A). During this interval, the Cameros Basin was a hanging-wall basin, which formed over a south-dipping ramp linking two flats in an extensional fault detachment that developed in the Variscan basement (Mas et al. 1993, Guimerà et al. 1995, Mas et al. 2002, 2003 and 2011). Due to its northwestern location in the Iberian Rift, this basin is characterized by minor marine influence and a delayed initiation to the extensional processes as the rift began in the southeastern part of the Iberian plate and spread to the north and west (Salas et al. 2001, Mas et al. 2002). However, subsidence was high and up to 6500 m of sediments were deposited in the depocenter (Mas et al. 2002, 2003 and 2011, Omodeo-Salé et al. 2014) in the eastern sector of the basin (E Cameros Basin), while in the western sector (W Cameros Basin; our study area) the maximum thickness does not reach one third of the thickness reached in the eastern sector (Fig. 1B). After this extensional period, the Cameros Basin was enclosed within the Iberian Basin from the Late Albian to Late Cretaceous in a thermal-subsidence regime (Alonso et al. 1993, Salas et al. 2001). Wide carbonate platforms developed during this period. Finally the basin experienced inversion during the Alpine Orogeny, acquiring the pop-up compressive structure (Fig. 1B) it currently displays, with a north-verging neoformed main compressional structure that thrusts the Cameros Basin structural unit onto the Cenozoic Ebro Basin and a south-verging secondary structure that thrusts the Cameros Basin structural unit onto the Duero-Almazán Basin (Fig. 1A and B) (Guimerà et al. 1995, Casas-Sainz et al. 2000).

The W Cameros Basin displays a current compressive structure consisting of a set of thrusts and folds with an NW-SE orientation (Fig. 1C) that is limited and cut by strike-slip faults with an NNE-SSW orientation (Beuther 1966, Salomon 1982, Platt

1990, Clemente and Pérez-Arlucea 1993, Guimerà et al. 1995, Martín-Closas and Alonso 1998, Sacristán-Horcajada et al. 2012c). This structure is actually the result of the inversion of an extensional structure consisting of a set of halfgrabens limited by NW-SE normal faults and linked by NNE-SSW transfer zones during the Alpine Orogeny (Platt 1990, Guimerà et al. 1995, Martín-Closas and Alonso 1998, Sacristán-Horcajada et al. 2012c). Three different sectors have been distinguished in the W Cameros Basin (Fig. 1C): the North Sector, with south-dipping thrusts, which include the area located to the south of the La Demanda Massif; the Central Sector, which includes the area around the north-dipping Moncalvillo Thrust; and the S Sector, which includes the area around the north-dipping San Leonardo Thrust and the South Cameros Thrust.

The syn-rift sedimentary infill of the Cameros Basin has been organized into eight depositional sequences (DS) limited by discontinuities (Fig. 2A). Due to the asymmetric geometry of the sedimentary basin fill (Mas et al. 2002, 2003, 2011; Omodeo-Salé et al. 2014), the fourth and eighth sequences were not recorded in the W Cameros study area (Fig. 2A and 2B). These sequences consist mostly of alluvial fans and fluvial and lacustrine sediments with occasional marine influence (Mas et al. 1993, 2002), but recently it has been found that the marine influence is more important and frequent than previously considered (Mas et al. 2011, Sacristán-Horcajada et al. 2012a, Sacristán-Horcajada et al. 2012b, Quijada et al. 2013, Suarez-Gonzalez et al. 2013).

Depositional Sequence 1 (DS1) in the W Cameros Basin

As previously stated, six of the eight depositional sequences can be distinguished in the W Cameros Basin (Fig. 2B), although they are less thick than in the eastern area of the basin (Clemente and Pérez-Arlucea 1993, Martín-Closas and Alonso 1998, Arribas et al. 2003). The earliest syn-rift sedimentary record (DS1) is represented by the clastic Nuestra Señora de Brezales Fm (Brezales Fm hereafter) and the carbonate Boleras Fm (Fig. 2) and form the focus of this study. Dating of these two formations is difficult due to the lack of useful microfauna; however, ostracod and charophyte assemblages have dated them as Tithonian (Martín-Closas and Alonso 1998, Schudack and Schudack 2009). Although the Brezales Fm changes gradually (both vertically and laterally) to the Boleras Fm, two episodes or stages can be distinguished in the sedimentary evolution of the Brezales - Boleras Formations that are represented by the stratigraphic record of Depositional Sequence 1 (Fig. 2B): the first (Stage 1) markedly clastic and dominantly represented by the Brezales Fm, and the second (Stage 2) distinctly carbonate and dominantly represented by the Boleras Fm.

METHODS

This study is based mainly on field work. Detailed geological mapping of different outcrops on a one – to – ten - thousand scales was performed with field observations, orthophotos, and aerial photographs. General large-scale geological mapping was also undertaken. Twenty-eight stratigraphic sections were studied and sampled in detail (Figs. 1C, 3, 4, 5). Sedimentary facies analysis was carried out using large- and medium-scale field observations and studying more than 100 polished hand specimens (Table 1). In the Brezales Fm paleocurrents were measured both in imbricated clasts and in cross-bedding, and data were statistically processed and graphically displayed both at different levels along the different sections (Fig. 6) and in each section for the entire Brezales Fm (Fig. 7) with PAST (Hammer et al. 2001). Petrographic analysis included transmitted-light microscope measurements of 267 polished and uncovered thin sections 30 μm thick. The thin sections were prepared using standard procedures including the following: (1) impregnation with blue epoxy resin to highlight porosity and (2) selective staining and etching to identify feldspar (Friedman 1971, Norman 1974) and carbonate (Lindholm and Finkelman 1972).

The analysis and correlation of the 28 sections describes the stratigraphic and sedimentological characteristics of the earliest syn-rift deposits (Depositional Sequence 1; Fig. 2), namely, the Brezales and the Boleras Fms.

RESULTS

Stratigraphy

The Brezales Fm overlies a major unconformity that developed on pre-rift marine Callovian to Kimmeridgian sandstones and limestones (Fig. 2B). This unconformity in the North and Central Sector of the study area developed on the Callovian limestones and sandy limestones (Pozalmuro Fm), and corresponds to a paleokarst that modified up to 20 m of the top of the pre-rift marine record. The unconformity in the South Sector of the study area developed on the Middle - Upper Jurassic sandstones and conglomerates (Pozalmuro, Aldealpozo, and Torrecilla en Cameros Fms) and corresponds to a complex pedogenic sequence with well-developed calcrete profiles.

The Brezales Fm is 5 to 222 m thick, displays great thickness differences, and is not present in all of the studied sections (Fig. 3). The greatest thickness of this formation is located in the North Sector, where it has four depocenters and reaches a maximum thickness of 222 m (VZ section; Fig. 3A and 3B), whereas its maximum thickness in the South Sector is only 56 m (BR section; Fig. 3B and 3D). The Brezales Fm consists of conglomerates, sandstones, sandy mudstones, and sandy limestones. The conglomerates are made of carbonate pebbles and sandy matrix with a quartzolithic composition. The sandstone levels have a similar composition to the matrix of the conglomerates, the mudstones are mainly siliciclastic with a considerable percentage of sandy grains (20 - 30%), and the sandy limestones are scarce and appear in thin nodular levels. The Brezales Fm changes gradually both vertically and laterally into the Boleras Fm.

The Boleras Fm is 2 to 116 m thick and, like Brezales Fm, displays great thickness variability and is not present in all of the studied sections (Fig. 3). Its thickest sedimentary record is located in the South Sector with a main depocenter 116 m thick (AR section; Fig. 3C and 3D), whereas it has a scarcer development in the North Sector.

When the Brezales Fm is not present, the Boleras Fm can directly overlie the unconformity that developed on the pre-rift marine Middle to Upper Jurassic sediments. The lithology consists of limestones with mudstone, wackestone and packstone textures; contains continental microfossil and macrofossil assemblages with charophytes, ostracods, gastropods, and bivalves, and is characterized by intense pedogenic modifications.

Sedimentology: Facies Associations

The study of the 28 stratigraphic sections and the analysis of the polished hand specimens and the thin sections have distinguished 13 sedimentary facies (8 clastic lithofacies, *sensu* Miall, 2010, and 5 carbonate lithofacies) whose main characteristics and related processes are summarized in Table 1. The most representative stratigraphic sections of the facies recorded in each halfgraben are shown in Figures 4 and 5. These sedimentary facies appear in the studied sedimentary record and are related to 12 different types of architectural elements (Fig. 8) *sensu* the meaning established by Miall (2010). In addition, these facies and architectural elements are associated with 7 distinct facies associations (Fig. 8) with different environmental significance within the recognized depositional systems. In addition, for each representative stratigraphic section shown in Figures 4 and 5, percentages of the various clastic architectural elements were calculated for the Brezales Fm (Fig. 9). The distribution of facies associations in each section has correlated the different stratigraphic sections (Fig. 10). Some field and microscope examples of the distinguished facies are illustrated (Figs. 11, 12). The facies associations and their environmental interpretation are described below.

Facies Association 1 (FA-1)

Sedimentary Characteristics

This facies association (1 in Fig. 4 A and FA-1 in Fig. 7) appears only in the lower half of the Vizcainos section in the northeastern outcrops of the North Sector (VZ in Fig. 10). It is characterized by the predominance of lenses and tabular bodies of clast-supported massive conglomerate with pebble imbrications (Gcm in FA-1 in Fig. 8) and planar and trough crossbed-stratified conglomerate (Gt and Gp in FA-1 in Figs. 8, 11A) related to in-channel gravel bars and gravel bed forms (GB in FA-1 in Fig. 8; VZ ST1 in Fig. 9) architectural elements, respectively. To a lesser extent this association also has sheets and channel-fill lenses of trough cross-bedded coarse sandstone (St in FA-1 in Fig. 8). This facies, which sometimes is not present due to erosion linked to the development of subsequent channels, appears interbedded with previous conglomeratic facies related to in-channel sandy bed forms architectural element (SB in FA-1 in Fig. 8; VZ ST1 in Fig. 9). Therefore, FA-1 is the result of the vertical stacking and coalescence of very coarse- and coarse-grained channelized bodies that form tabular thick and extensive (almost few kilometers of transverse lateral extent) bodies (CH in FA-1 in

Fig. 8). The paleocurrent data measured in the imbricated pebbles and cross-bedding display a relatively wide dispersion and indicate a mean SW orientation (Figs. 6, 7).

Environmental Interpretation

This association is interpreted as the result of the sedimentation of channelized coarse bedload transport deposits as a braided channel system on the proximal portion of an alluvial-fan system dominated by stream-flow channelized processes and characterized by a good proximal - distal environmental gradation. Specifically, it represents the inner part of a fan-shaped alluvial system characterized by coarser gravel deposits (Rust 1979, Nichols and Fisher, 2007, Colombo 2010). The characteristics of the deposits indicate that sediment transport in this alluvial system took place through a distributive network of channels, which were braided in the proximal environments with higher slopes. The scarce development of calcretes on the proximal facies indicates relatively continuous sedimentation throughout the whole area of the fan, which did not allow the establishment of stable surfaces (Allen and Wright 1989, Alonso-Zarza et al. 1992). This is interpreted as a consequence of the constant lateral migration of the channels, which indicates the unsteadiness of the proximal braided network (Rust 1979). All of these characteristics suggest that this association is the inner part of a highly channelized alluvial fan system (FA-1 in Fig. 13), which could also be considered a relatively small distributary “fluvial fan system” (*sensu* Nichols and Fisher, 2007) or even a “small to very small distributive fluvial fan system” (DFS *sensu* Hartley et al. 2010 and Weissmann et al. 2010).

Facies Association 2 (FA-2)

Sedimentary Characteristics

This facies association (2 in Fig. 4 and FA-2 in Fig.8) also appears only in the lower half of the Vizcainos section (VZ in Fig. 10). It is characterized by tens of meters-wide lenses of trough cross-bedded conglomerates (Gt in FA-2 in Figs. 8, 11B) and trough cross-bedded sandstone (St in FA-2 in Fig. 8), which are commonly organized as medium- to large-scale lateral-accretion forms (LA in FA-2 in Fig. 8, VZ ST1 in Fig. 9, Fig. 11B) in concave-up erosionally based channel bodies (CH in FA-2 in Fig. 8 and Fig. 11B). An increase in the amount of mica grains and metamorphic lithic fragments is observed in the channelized sandstone facies at the top of the association. Channel deposits are dispersed within relatively thick (several meters to tens of meters) extensive sheets of massive siliciclastic mudstone that is often sandy and displays root traces and edaphic carbonate concretions (Fmr in FA-2 in Fig. 8 and Fig. 11B). They often contain intercalations of thin sheets of cross-laminated fine sandstone and paleosol carbonate layers (calcretes) with low lateral continuity and pedogenic features such as nodular, massive, and laminar morphologies (P in FA-2 in Fig. 8). These relatively thick tabular units composed of finer facies and are related to the floodplain fines architectural elements (FF in FA-2 in Fig. 8; VZ ST1 in Fig. 9; and Fig. 11B). The paleocurrent data measured in imbricated pebbles and cross-bedding in the channelized bodies display wider dispersion than the previous association and also indicate a mean SW orientation (Figs. 6, 7).

Environmental Interpretation

This association is interpreted as the result of the sedimentation of sinuous, channelized coarse bedload transport (meandering channels) and vertical floodplain accretion deposits in the medial to distal portion of an alluvial fan system dominated by stream-flow channelized processes and characterized by a good proximal - distal environmental gradation. The association represents the outer part of a fan-shaped alluvial system characterized by finer deposits (Rust 1979, Nichols and Fisher 2007, Colombo 2010). The characteristics of the deposits indicate that sediment transport in this alluvial system took place through a distributive network of dominantly meandering channels in more distal environments in the fan where the slopes were lower. The better development of calcrete deposits in this distal environment indicates the relative stabilization of the channel network in these areas of the fan (Allen and Wright 1989, Alonso-Zarza et al. 1992). These characteristics suggest that this association is the outer part of a highly channelized alluvial fan system (FA-2 in Fig.13), which could also be considered a relatively small "distributary fluvial fan system" (*sensu* Nichols and Fisher 2007) or even a "small to very small distributive fluvial fan system" (DFS *sensu* Hartley et al., 2010, Weissmann et al. 2010).

Facies Association 3 (FA-3)

Sedimentary Characteristics

This facies association (3 in Fig. 4 and FA-3 in Fig. 8) appears in the upper half of the Vizcainos section (3 in Fig. 4 and VZ in Fig. 10) and in the Terrazas 1 section (TR 1 in Fig. 10) and Terrazas 2 section (Fig. 4 and TR 2 in Fig. 10). It is mainly characterized by erosionally based tabular bodies of moderately sorted conglomerates with first-order (sets 1.5 to 3 m thick), large-scale planar cross-bedding (Gp in FA-3 in Fig. 8) and sometimes second-order, smaller-scale trough cross-bedding (Gt in FA-3 in Fig. 8) both corresponding to gravel bedforms architectural elements (GB in FA-3 in Fig. 8; VZ ST2 and TR2 in Fig. 9; Fig. 11C). Less common flat-bedded and trough cross-bedded sandstone (Sh and St in FA-3 in Fig. 8), which form sheets and channel-fill lenses sandy bedforms architectural elements (SB of FA-3 in Fig. 8; VZ ST2 and TR2 in Fig. 9), may be associated with the conglomeratic facies. These conglomerate and sandstone facies organized as coalesced braided channel bodies that result in extensive thick tabular bodies (CH in FA-3 in Fig. 8). Evidence of subaerial exposure (pedogenesis) on the top of some first-order sets and occasional intercalations of fine sediments and generally sandy siliciclastic mudstone with carbonate pedogenesis (calcretes), is also recorded (Fmr in Table 1 and in FA-3 in Fig. 8). The paleocurrent data measured from imbricated pebbles and cross-beds display a wider dispersion in the Vizcaínos section (VZ), which indicates a mean SW orientation perpendicular to the fault that controls the Vizcaínos halfgraben, than in the Terrazas 2 section (TR 2), they indicate a mean E to SE orientation (Figs. 6, 7) parallel to the fault that controls the Vizcaínos halfgraben. Moreover the Brezales Fm isopachs in the Vizcaínos area have a fairly circular shape, while those in the Terrazas area (TR 1 and TR 2) have a roughly E-W elongated shape (Figs. 3B, 7).

Environmental Interpretation

This association is interpreted as the result of the sedimentation of channelized coarse- to medium-grained bedload transport deposits (perennial braided channels). This facies association corresponds to the paleo-channels (braided channels) of a distributary fluvial fan system (FA-3 in Fig. 13) at Vizcaínos area (*sensu* Nichols and Fisher, 2007) or even a “small to very small distributive fluvial fan system” (DFS *sensu* Hartley et al., 2010 and Weissmann et al., 2010) changing downstream at the Terrazas area to a braided river (AS-2 in Fig. 13), which represent an “axial tributary fluvial system” (*sensu* Fielding et al. 2012).

Facies Association 4 (FA-4)

Sedimentary Characteristics

This facies association (4 in Figs. 4, 5; FA-4 in Fig. 8) is recorded in the lowest part of the Jaramillo, Rupelo, Quintanilla, and Arroyo del Helechal halfgraben basins (Fig. 10). All of these halfgrabens were controlled by normal faults (now inverted), limiting the corresponding basins to the north (Fig. 7). This association is characterized by the presence of both mass-flow and stream-flow facies and by a poor facies gradation. It consists of lobes or sheets of matrix-supported massive or graded gravel (paraconglomerate with predominantly muddy and sometimes rather sandy matrix; Gmm and Gmg in FA-4 in Fig. 8) corresponding to plastic and pseudoplastic debris-flow deposits, i.e., sediment gravity flows architectural elements (SG in FA-4 in Fig. 7; RU, JQ and AHE in Fig. 9; Fig. 11D; Fig. 11E) which are generally overlain and frequently eroded by cross-bedded gravel (orthoconglomerate; Gp and Gt in FA-4 of Fig. 8) corresponding to small, gravelly, minor channel infilling and bars architectural elements (CH and GB of FA-4 in Fig. 8). Occasionally, some flat-bedded or trough cross-bedded sandstone beds (St in FA-4 in Fig. 7) corresponding to small, sheet-shaped and channel-fill lens sandy bedforms small architectural elements (SB in FA-4 in Fig. 8) and even some very occasional intercalation of siliciclastic mudstone (Fmr in FA-4 of Fig. 8) representing occasional flood-plain fines (FF of FA-4 in Fig. 7) may be also present. Well-developed and thick calcrete deposits with laminar morphologies (P in FA-4 of Fig. 7) occur on all types of sedimentary facies and increase in thickness and complexity toward the top of the sedimentary records of the associations (Fig. 9F). In addition, mass-flow deposits are more abundant at the bottom of this facies association sedimentary records. The paleocurrent data measured in imbricated clasts and cross-bedding display wide dispersion and indicate a mean SW-WSW orientation (Figs. 6, 7).

Environmental Interpretation

This association is interpreted as the result of clastic sedimentation in alluvial fan systems in which both debris-flow deposits related to ephemeral mass-flow transport and poorly channelized coarse-bedload deposits related to also ephemeral stream-flow processes are present. The development of superimposed calcrete developing (highly developed or mature calcrete), which nearly completely modified the aforementioned deposits, would indicate an intermittent or very episodically discontinuous alluvial fan (Allen and Wright 1989, Alonso-Zarza et al. 1992). Specifically, this facies association represents the most proximal environment or inner fan body in a poorly channelized ephemeral alluvial fan system (AS-3 in Fig. 13) characterized by debris-flow deposits and minor, small channel deposits (Rust 1979, Nilsen 1982, Nichols and Fisher 2007, Colombo 2010).

Facies Association 5 (FA-5)

Sedimentary Characteristics

This facies association (5 in Figs. 4, 5; FA-5 in Fig. 8) is recorded above FA-4 and below FA-6 facies association in the lower part of the Jaramillo and Rupelo halfgraben basins in the North Sector and in FA-6 in approximately the middle of the Mamolar and Brezales halfgraben basins at the South Sector (5 in Figs. 4, 5; Fig. 10). The North Sector halfgrabens were controlled by normal faults (now inverted) that limited the corresponding basins to the north, whereas the South Sector halfgrabens were controlled by normal faults (now inverted) that limited the corresponding basins to the south (Fig. 7). This association consists of massive or cross-bedded gravel (orthoconglomerate; Gcm, Gp and Gt in FA-5 in Fig. 8 and Fig. 12A) corresponding to gravel bars and bedforms (GB in FA-5 in Fig. 8; RU, JQ, MAN and BR in Fig. 9), flat-bedded and cross-bedded sandstone beds (Sh and St in FA-5 of Fig. 8) presented as sheet-shaped sandy bedforms (SB in FA-5 in Fig. 8; RU, JQ, MAN and BR in Fig. 9), and both conglomeratic and sandy facies are related to scarce and small channels (CH in FA-5 in Fig. 8). This facies association also presents siliciclastic mudstone, commonly sandy mudstone (Fmr in FA-5 in Fig. 8) present as relatively extensive tabular sheets a few meters to several meters thick corresponding to floodplain fines (FF of FA-5 in Fig. 7; RU, JQ, MAN and BR in Fig. 8). As in the previous facies association (FA-4), all types of sedimentary facies in this association display superimposed, well-developed and thick calcrete deposits with nodular, laminar, massive, and even brecciated - pisolitic fabrics (P in FA-5 of Fig. 8, Fig. 12B). Moreover, the FA-4 association shows a gradual change in its facies with this association. The paleocurrent data measured in imbricated clasts and cross-bedding display a wide dispersion and indicate a mean SW-WSW orientation for the North Sector halfgraben basins and a mean NE-ENE orientation for the South Sector halfgraben basins (Figs. 6, 7).

Environmental Interpretation

This association is also interpreted as the result of clastic sedimentation in alluvial fan systems in which both poorly channelized and sheet-flood coarse- to medium-bedload deposits related to ephemeral stream-flow processes and vertical-accretion deposits related to settling from the suspension of fines are present. As in the previous association, common superimposed mature calcretes developed and nearly completely modified these sediments, suggesting an intermittently functioning alluvial fan (Allen and Wright 1989, Alonso-Zarza et al. 1992). In the halfgraben basins of the North Sector this association represents the medial environment or mid-fan body in a poorly channelized ephemeral alluvial fan system (AS-3 in Fig.13) characterized by ephemeral channelized and nonchannelized stream flows and, frequently, largely exposed vertical-accretion flood environments (Rust 1979, Nilsen 1982, Nichols and

Fisher 2007, Colombo 2010). In the halfgraben basins of the South Sector, where the previous facies association (FA-4) is not present, this association could represent the most proximal environment or inner-fan body of this poorly channelized ephemeral alluvial fan system (AS-3 in Fig.13).

Facies Association 6 (FA-6)

Sedimentary Characteristics

This facies association (6 in Figs. 4, 5; FA-6 in Fig. 8) is recorded in all of the halfgraben basins in the study area and represents by far the largest volume of sediment in the set of all facies associations. It consists of red sandy siliciclastic mudstone deposits that commonly display root mottling and root traces and very thin intercalations of parallel- and cross-laminated fine to very fine sandstone (Fmr in FA-6 in Fig. 8) constituting thick and extensive sheets (hundreds to thousands of meters wide and tens of meters thick) of floodplain deposits (FF of FA-6 in Fig. 8; Fig. 10). Superimposed carbonate paleosol levels with nodular, massive, and laminar fabrics (P in FA-6 of Fig. 8) are intensely developed, forming thick pedogenic calcretes (PC in FA-6 in Fig. 8) that completely modified the original sedimentary deposits in most sections (Fig. 12C). Occasionally, flat-bedded and/or cross-bedded sandstones appear intercalated (Sh and St in FA-6 in Fig. 8 and Fig. 12D) as poorly channelized or nonchannelized isolated beds (CH, LS and SB in FA-6 in Fig. 8). These isolated beds also show superimposed calcretes on top. This facies association is laterally and vertically related to many other (Figs. 4, 5, 10).

Environmental Interpretation

This association is interpreted as periodically prolonged, exposed floodplain vertical-accretion deposits (settling from the suspension of fines) and occasionally poorly channelized to non channelized medium-grained bedload transport deposits related to ephemeral streams. Common superimposed calcrete developed (commonly mature pedogenic calcrete) and nearly completely modified the sediments of this association, indicating the intermittently discontinuous nature of the depositional system with prolonged episodes of non deposition (Allen and Wright 1989, Alonso-Zarza et al. 1992, Daams et al. 1996). This facies association is related to different flood-plain environments (FA-6 in Fig. 13) in the different depositional systems where it is present (fluvial flood-plains or distal alluvial fans, alluvial-fan toes, and peri-lacustrine palustrine environments).

Facies Association 7 (FA-7)

Sedimentary Characteristics

This facies association (7 in Figs. 4, 5; FA-7 in Fig. 8) corresponds to the Boleras Fm and is recorded in all of the halfgraben basins in the study area except in the of Vicaínos halfgraben basin (Fig. 10). Usually, it occupies the uppermost part of the sedimentary record in these halfgraben basins, displaying gradual vertical and lateral facies changes along FA-6 (Stage 2, Fig. 10). However, in the southernmost halfgraben basin (Huerta del Rey halfgraben), where only the Stage 2 is recorded (Fig. 10), this facies association reaches an important thickness and constitutes the entire sedimentary record (Figs. 3C, 10). It consists of the vertical stacking of elementary sequences including, from base to top, well-bedded bioclastic limestones (Fig. 12E), massive limestone (Fig. 12F) and nodular limestones (Fig. 12F), corresponding to the Lb, Lm and Ln facies, respectively, in FA-7 in Fig. 7; and marl and marly mudstone with calcrete development (Mr and P, respectively, in FA-7 in Figs. 8 and 12F). All of these facies are not always present, resulting in one facies dominating in each part of the same section; e.g., well-bedded bioclastic limestones (Lb in FA-7 of Fig. 8) rarely appears and only in sections where this facies association experienced great development, which occurred in the Huerta del Rey halfgraben basin (e.g., Camino Forestal section in Fig. 5; CF and AR sections in Fig. 9).

Environmental Interpretation

Generally in this facies association FA-7 (Fig. 8) the limestone facies appears as extensive tabular bodies of continental carbonates (CTB in FA-7 in Fig. 8) with shallow lacustrine and palustrine units (SLC and PLC, respectively, in FA-7 in, while marly units represent peri-lacustrine palustrine, mixed, fine siliciclastic - carbonate floodplains (MF in FA-7 in Fig. 8). The lack of deep lacustrine facies and the intense pedogenic modifications indicate carbonate sedimentation in very shallow, periodically desiccated lakes (Arribas et al. 1983; Arribas 1986; Tucker and Wright 1996; Fregenal and Meléndez 2010) or a carbonate, shallow lacustrine - palustrine system (Freytet and Plaziat 1982, Platt and Wright 1991, Arribas et al. 1996, Freytet and Verrecchia 2002, Alonso-Zarza and Wright 2010a). Note that these palustrine-lacustrine systems appear to be laterally associated with the smaller poorly channelized alluvial fan systems (AS-3 in Fig. 13) in the North Sector (Quintanilla, Rupelo, and Jaramillo halfgraben basins) and South Sector (Arroyo del Helechal, Mamolar, and Brezales halfgraben basins) (Fig. 8) but do not appear to be related to the larger, highly channelized alluvial fan system or fluvial distributary fan system (AS-1 and AS-2 respectively in Fig. 13) of the Vizcaínos halfgraben basin (Fig. 9). In the Huerta del Rey halfgraben basin (Fig. 10) these palustrine - lacustrine systems are fully developed (Stage 2) with negligible clastic sediment load.

DISCUSSION

Types of Alluvial Systems

Considering the various facies associations and their lateral and vertical changes, three types of alluvial systems were distinguished in the studied sedimentary record (Fig. 13): a highly channelized alluvial fan system (AS-1); a fluvial distributive fan system that changes downstream to a tributary fluvial system (AS-2); and a poorly channelized alluvial fan system (AS-3).

Highly Channelized Alluvial Fan System (AS-1)

This type of alluvial system is characterized by facies associations FA-1 and FA-2 (Figs. 13, 14) and was developed during the Stage 1 in the Vicaínos halfgraben basin. This could be considered a relatively small "fluvial distributary fan system" (*sensu* Nichols and Fisher, 2007) or even a "small to very small distributive fluvial fan system" (DFS *sensu* Hartley et al., 2010, and Weissmann et al., 2010). This is an alluvial system fed by bedload transport under channelized tractive currents with proximal braided channels that change to meandering towards the distal parts. Its sedimentary record presents two sequences with retrograding depositional architecture or alluvial-fan retraction (Fig. 10). Its maximum area is approximately of 100 km^2 and, together with the alluvial system that developed during the Stage 2 in this halfgraben basin (Vizcaínos halfgraben), is the most extensive fan-shaped alluvial system identified in the study area (Fig. 3B). The paleocurrents display relatively wide dispersion and indicate a mean SW orientation (Figs. 6, 7). The drainage area of this alluvial fan system is located to the north in the footwall of the normal fault (now inverted), which bounds by the north and controls the sedimentary fill of Vizcaínos halfgraben basin (Fig. 15A).

Distributive Fluvial Fan System (Braided Channels) Changing Downstream to an Axial Tributary Fluvial System (Braided River) (AS-2)

This type of alluvial system is characterized by facies associations FA-3 and FA-6 (Figs. 13, 14). It is a fan-shaped distributary system of braided channels ("fluvial distributary fan system" *sensu* Nichols and Fisher 2007) or even a "small to very small distributive fluvial fan system" (DFS *sensu* Hartley et al. 2010, and Weissmann et al. 2010) that joins an axial tributary braided river downstream (*sensu* Weissmann et al. 2010, Fielding et al., 2012). This alluvial system was fed by bedload transport under braided channelized perennial tractive currents. It was developed during the Stage 2 in the Vicaínos halfgraben basin and presents a prograding - retrograding (expansion - retraction) depositional architecture (Fig. 10). The maximum area of the fluvial distributary system is approximately 100 km^2 and, together with the alluvial system that developed during Stage 1 in this halfgraben basin, is the most extensive fan-shaped alluvial system identified in the study area. The paleocurrents display wider dispersion in the "Vizcaínos fluvial distributary fan system", indicating a mean SW orientation, compared to in the "Terrazas tributary fluvial system", which indicates a mean E to SE orientation (Figs. 6, 7). Moreover, isopachs of the Brezales Fm in the Vizcaínos fan area have a fairly circular shape, while those in the Terrazas area have a roughly E-W, elongated prismatic shape (Figs. 3B, 7), highlighting the shift from a fluvial distributary fan in the Vizcaínos area (VZ) to a tributary braided river in the Terrazas area (TR). The drainage area of this alluvial system is located to the north in the footwall of the normal fault, which bounds by the north and controls the sedimentary fill of the Vizcaínos halfgraben basin (Fig. 15B).

Poorly Channelized Alluvial Fan System (AS-3)

This type of alluvial system is characterized by facies associations FA-4 to FA-7 (Figs. 13, 15). It was fed by ephemeral mass-flows and/or bedload transport under poorly channelized to nonchannelized tractive currents. Their areal sizes are small, always smaller than those in the AS-1 and AS-2 alluvial systems, and vary between approximately 15 and 40 Km^2 (Figs. 3B, 7). Given these characteristics, perhaps this type of alluvial systems is the only one of the three that really should be considered as authentic alluvial fans (*sensu* Blair and McPherson, 1994a, 1994b); AS-1 and particularly AS-2 should be considered as simple, unconfined fan-shaped river systems. These types of alluvial fans (AS-3) were deposited in all of the halfgraben basins developed during Stage 1, except in the Vizcaínos halfgraben basin. Their sedimentary record presents both prograding (alluvial-fan expansion) and retrograding (alluvial-fan retraction) depositional architectures (Fig. 10). The halfgraben basins of the North Sector were controlled by normal faults (now inverted), which bounds the corresponding basins to the north, and their sedimentary records present retrograding architectures. However, the halfgraben basins of the South Sector were controlled by normal faults (now inverted), which limited the corresponding basins to the south, and their sedimentary records present prograding architectures (Fig. 10). The exception is the Arroyo del Helechal halfgraben basin, which was controlled by a normal fault that bounds the basin to the north, and its sedimentary record presents a retrograding depositional architecture. The drainage areas of these alluvial fan systems must have been of very small size and are located in the footwalls of the normal faults, which limited and controlled the sedimentary fill of the halfgraben basins both to the halfgrabens both the North Sector and the South Sector, except for the Arroyo del Helechal halfgraben, which was located to the north (Fig. 15A).

Early Syn-Rift Paleogeography

Paleogeographic Evolution

The stratigraphic correlation (Fig. 10) and sedimentological studies confirm that sedimentation took place in different sets of halfgrabens limited by belts of WNW-ESE extensional structures during the earliest syn-rift stages in the W Cameros Basin (Figs. 10, 15). The orientation of the alluvial systems indicated by paleocurrent measurements (Figs. 6, 7) and the stratigraphic and sedimentological differences previously described allow two paleogeographic sectors to be distinguished that coincide with the current geographical sectors: a North Sector (Figs. 10, 15) characterized by the S-oriented and sedimentological heterogeneous alluvial systems that are predominantly small (“poorly channelized alluvial fans”, AS-3 in Fig. 13) or large (“highly channelized alluvial fan” and “fluvial distributary fan”, respectively AS-1 and AS-2 in Fig. 13), a predominantly retrograding depositional architecture and the scarce development of the lacustrine environments; and a South Sector (Figs. 10, 15) characterized exclusively by small alluvial systems (“poorly channelized alluvial fans”, AS-3 in Fig. 13), a predominantly prograding depositional architecture and better developed lacustrine systems. Both sectors can be organized into two evolutionary stages: Stage 1, characterized by the development of alluvial systems (Fig. 15A), and Stage 2, characterized by the extensive development of lacustrine - palustrine systems (Fig. 15B). However, the sedimentological characteristics of each stage are different in each sector.

During Stage 1, the study area was characterized by the development of a set of WNW-ESE oriented halfgraben basins (Fig. 15A). The halfgraben basins of the North Sector were controlled by normal faults, which bound the corresponding basins to the north, and their sedimentary records display a retrograding geometry (Fig. 10). Small, poorly channelized alluvial fans (AS-3 in Fig. 13, Fig. 15A) that discharged their load of sediment to the S-SW (Fig. 7) and are distally associated with small lacustrine - palustrine carbonate systems developed in practically all of the basins (Fig. 15A). However, in the Vizcaínos basin, which was also controlled and bounded by a fault to the North and had a retrograding fill, a larger distributive fluvial fan (AS-1 in Fig. 13) developed with a higher discharge of siliciclastic sediment, which should not allow the formation of a distal lacustrine-palustrine carbonate system (Fig. 15A). The halfgraben basins of the South Sector were controlled by normal faults, which bound the corresponding basins to the south, and their sedimentary record displays a prograding geometry (Fig. 10). Small, poorly channelized alluvial fans (AS-3 in Fig. 13, Fig. 15A) that discharged their load of sediment to the N-NE (Fig. 7) and are not distally associated with small lacustrine - palustrine carbonate systems developed in all of these basins (Fig. 15A). The Arroyo del Helechal halfgraben basin is an exception, although a poorly channelized alluvial fan that was controlled and bounded by a fault to the north developed here, its sedimentary record is retrograding and the paleocurrents in the alluvial system indicate discharge to the S-SW. The drainage areas of these small and poorly channelized alluvial fan systems in both the North and South Sectors were located in the footwalls of normal faults that bounded and controlled their sedimentary fill (Fig. 15A). Nevertheless, in the Vizcaínos halfgraben basin, which was controlled and bounded by a normal fault in the north, the much larger and different type of alluvial system (AS-1 in Fig. 13) indicates that the drainage area in the footwall of that fault must have had much greater extent (Fig. 15A).

Remarkable changes in the paleogeography of the study area took place during Stage 2. Muddy flood plains and lacustrine - palustrine carbonate environments overstepped the small poorly channelized alluvial fans in the North Sector (Fig. 10; AS-3 in Fig. 13) (Rupelo, Quintanilla, and Jaramillo halfgraben basins, Fig. 15B). However, in the Vizcainos halfgraben basin, Stage 2 was characterized by the development of a new, large prograding - retrograding fan-shaped alluvial system, which corresponds to a fluvial distributary fan system (*sensu* Nichols and Fisher, 2007; or “small to very small distributive fluvial fan system” DFS *sensu* Hartley et al. 2010 and Weissmann et al. 2010) that changes southeastward and downstream to an axial (WNW-ESE) tributary fluvial system (Fig. 15B). This fact reveals that this halfgraben basin was the only structure still receiving considerable input clastic sediment during the second evolutionary stage. During Stage 2, the sedimentation in the South Sector was controlled by a different extensional structure located more to the south than those that had controlled the previous stage and coincide with the current South Cameros Thrust (Fig. 15B). The sedimentation in this new halfgraben basin (Huerta del Rey halfgraben basin) was mainly carbonate lacustrine - palustrine and more extensive to the point that the lacustrine - palustrine sediments fossilized the previous small alluvial fan systems related to the older halfgrabens (Figs. 10, 15B). Considering the negligible clastic sediment load arrival to this southernmost halfgraben basin and the thick sedimentary record of lacustrine - palustrine micritic limestone in the basin (Stage 2; Figs. 10, 15B), these carbonate lakes and wetlands, where a very high rate of organic carbonate production took place, likely were not laterally connected with alluvial fans to the south or, if so, limited the development of these alluvial fans. Thus, carbonate water would reach the basin from carbonate water springs associated with a karst system that developed in the footwall of the main fault that bounds the Huerta del Rey halfgraben basin to the south and controlled its development; therefore, this halfgraben basin should be considered a karstic drainage area.

Factors Controlling Paleogeography

The main general factors controlling the processes and sedimentary architecture of alluvial fans and, in general, of fan-shaped alluvial systems related to extensional basins are as follows: drainage area (bedrock lithology, shape, and size), tectonics and climate (Miall 1981, Rust 1981, Nilsen 1982, Harvey 1990, Lecce 1990, Blair and McPherson 1994b, Anderson and Cross 2001, Harvey 2005, Miall 2010). In studies of fossil sedimentary records, the drainage-area lithology can be deduced from the size and facies arrangement of the depositional system and the analysis of the provenance of its clastic sedimentary rocks. However, the relative size of the drainage area occasionally only can be indirectly inferred from the comparative study of the size of the various alluvial systems generated from the functioning of equivalent tectonic structures in the fossil record, and its shape would be virtually impossible to deduce. Tectonics is directly related to subsidence and paleotopography, mainly influencing the shape, morphology, thickness and drainage pattern of the alluvial systems and their associated distal systems (Lecce 1990, Blair and McPherson 1994a and 1994b, Schumm et al. 2000; Colombo 2010). Climate is directly related to rainfall and net water availability, influencing weathering rates, sediment generation, and the magnitude, frequency and types of sedimentary processes (Rust 1981, Lecce 1990, Maizels 1990, Blair and McPherson 1994a and 1994b, Colombo 2010, Allen et al. 2013).

Climate

The great development of calcrete profiles in the study area implies a semiarid climate involving the seasonal alternation of short wet and long dry periods (Tucker and Wright 1996, Alonso-Zarza and Wright 2010b). Calcretes also imply an approximate rainfall amount. Although calcretes have been reported in climates with rainfall averages ranging from 50 to 1000 mm/year (Alonso-Zarza and Wright 2010b), the most favorable rainfall averages for formation of thick, well-developed calcretes like those described in this work range between 100 and 500 mm/year (Goudie 1983). This semiarid seasonal climate is also favorable for the development of lacustrine - palustrine systems characterized by great water-level fluctuations and periodic episodes of desiccation like those described in the study area. These interpretations agree with the climate described for western Europe during the Tithonian. The climate during that time interval changed from the more humid conditions in the middle Jurassic to more arid conditions (Ruffell and Rawson 1994). It has been observed that this change was paleogeographically diachronous, whereas conditions of true aridity were established during the Late Oxfordian to the Kimmeridgian in eastern Europe, the conditions never became more extreme than semiarid and seasonal until the end of the Jurassic in western Europe (Francis 1984, Hallam 1984, Ruffell and Rawson 1994, Rees et al. 2004, Parrish et al. 2004).

Climate has been often targeted as responsible for changes in the geomorphology and hydrology of alluvial systems (Rust 1979, Rust 1981, Nilsen 1982, Lecce 1990, Maizels 1990, Blair and McPherson 1994a and 1994b). In fact, in a semiarid region, such as that inferred for the sedimentary record of this study area, coarser deposits would be deposited by discrete, high-magnitude floods that occurred only sporadically because of the infrequent nature of rainfall without having to invoke the tectonic destabilization of the alluvial system as a cause of influx of coarser alluvial deposits (Frostick and Reid, 1989a). Moreover, climate plays an important role in the organization of the alluvial depositional systems in rifts; for example, in the present-day rift systems in arid and semiarid regions (e.g., African and North Basin and Range province, USA, dryland rifts), axial rivers contribute little sediment to these dryland basins, and deposits from transverse drainages dominate the rifts. Therefore, one must take care in interpreting the fossil record of alluvial systems under arid and semiarid climates, and a larger role for transverse alluvial systems should be considered as a major contributor of sand and coarser sediment to dryland rift basins (Frostick and Reid 1989b, Fordham et al. 2010). However, this study focuses on depositional systems that developed in the same, relatively small region; therefore, climate can be considered homogeneous throughout the study area. Great calcrete development during both paleogeographic stages (Figs. 4, 5, 15) also indicate that climate did not change significantly during the time interval studied. Thus, climate cannot be responsible for the sedimentological and architectural differences previously described, as its effects over weathering, sediment supply, and transportation type can be considered homogeneous and other factors such as the lithology and size of the drainage area, and tectonics must be considered as the main factors responsible for this sedimentary heterogeneity.

Drainage Area: Lithology and Size

The drainage area of an alluvial system is the area drained and weathered by the streams that formed the alluvial fans (Nilsen 1982, Colombo 2010) and the fan-shaped alluvial systems called “distributive fluvial fans” (DFS *sensu* Hartley et al. 2010 and Weissmann et al. 2010). Sediments in small halfgraben basins related to extensional tectonic settings are usually locally derived and so reflect the local lithological variation of the substrate (Miall 1981).

Arribas et al. (2003) studied the provenance of the detritic sediments in the West Cameros Basin and concluded that the composition of the alluvial Brezales Fm indicated that the underlying marine pre-rift Jurassic sediments were the main source rocks for this formation and that the lithological composition and grain-size characteristics of the clastic sediments reflect the lithological variation of this pre-rift Jurassic substrate. These conclusions are consistent with the lithological and grain-size differences observed in this work. In the North Sector, the predominance of carbonate clasts in the coarser facies and the quartzolithic composition of most of the sandstone facies reflect the erosion of the marine pre-rift Callovian limestones and sandy limestones. However, the limited amounts of carbonate rock fragments, the higher content of clastic lithic fragments and quartz grains, and the generally finer grain size in the South Sector reflect the predominance of sandy siliciclastic deposits in the underlying pre-rift Jurassic sediments. The local increase in micas, feldspar, and metamorphic rock fragments in the North Sector noted by Arribas et al. (2003) has been observed in four of the sections in the North Sector (VZ, CTV, TR1 and TR2, Fig. 2).

Despite this lithological variation, all of the alluvial systems were fed by drainage areas that developed on soft, easily eroded sedimentary rocks; therefore, the stratigraphical and sedimentological differences described here cannot have originated from differences in the composition of the source area. Lithological controls, however, can be considered responsible for some specific characteristics of the fans, like the lack of mass-flow processes in some alluvial systems in the South Sector (Mamolar and Brezales Halfgraben, Fig. 10). Debris flows were promoted by short periods of abundant water supply (Bull 1972); thus, the climatic characteristics described in the previous section were appropriate for this type of processes, and support their presence in other alluvial systems in the North and the South Sectors. Thus, lithological factors must be considered as the cause of this lack of mass processes in some of the alluvial systems. The pre-rift substrate of the South Sector, consisting of quartzarenitic sandstones and minor conglomerates cemented by carbonate, did not favor production of fine sediment; therefore, the lithology of the source area can be addressed as the cause of the lack of facies representing mass-flow deposits (Blair and McPherson 1994 a, 1994b). This mainly fine- to mid-size siliciclastic lithology of the source area can also be related to the scarce development of the coarser proximal facies in the north-oriented alluvial systems in the South Sector. This interpretation also agrees with the fact that mass-flow deposits do appear in the alluvial sedimentary record of the Helechal halfgraben, the only south-oriented alluvial system in the South Sector (AHE, Fig. 15A), which also display a coarser grain size, a better developed proximal facies and high amounts of carbonate clasts and other lithic fragments. All of this indicates that this south-oriented alluvial system had a drainage area with a lithological composition different from that of the north-oriented systems, which were probably similar in composition to the source area of the northern alluvial system. The lithology of the drainage area was also an important factor that controlled the hydrochemistry of both runoff water and groundwater. The water was supplied to the basin from different carbonate source areas (predominantly marine Jurassic beds of limestone and to a lesser extent calcareous sandstone) and was strongly supersaturated with respect to calcium carbonate. This factor in conjunction with the semiarid climate very widely promotes the rapid and significant development of pedogenic calcretes on different temporarily inactive (no sedimentation) alluvial-system environments that developed, in turn, upon different architectural elements (floodplain fines, channels, gravelly and sandy bedforms sheets, and debris-flow lobes). These temporarily inactive areas could eventually be located on relatively proximal and even proximal alluvial-fan areas, as evidenced by some of the types of sediments on which pedogenic calcretes were developed (e.g. superimposed on debris-flow and sheet-flow deposits). This is not so unusual in semiarid regions, such as SE Spain, where there are good examples of pedogenic calcretes developed on proximal areas of Quaternary alluvial fans (Alonso-

Zarza et al., 1998; Stokes et al., 2007). As previously noted during the Stage 2 sedimentation in the Huerta del Rey halfgraben basin (the southernmost halfgraben basin controlled and bounded by a normal fault to the south) was mainly carbonate lacustrine - palustrine with almost negligible arrival of clastic sediment load (Figs. 3, 15B), indicating that these carbonate lakes and wetlands were not laterally connected with alluvial the fans to the south or, if so, limited the development of these alluvial fans, and water would get into this basin from springs of carbonated water associated with a karst system to the south.

Catchment size is a very important control on rift basin-fill successions (Lambiase and Morley, 1999; Viseras, et al., 2003; Fordham et al., 2010; Leleu and Hartley, 2010). In the studied record of the W Cameros Basin, the size of the drainage areas played an important role in controlling the type of associated alluvial systems in the halfgraben basins and could also play an important role in controlling the amount and type of sediment input to these extensional basins. As previously mentioned in the section “Types of alluvial systems”, the drainage areas of the small and poorly channelized alluvial-fan systems had to be of very small size (AS-3 in Fig. 13; Fig. 15 A), and most likely all of these drainage areas were located in the same semiarid climate zone. However, in the Vizcaínos halfgraben basin (in the northern edge of the rift system), which was controlled and bounded by a normal fault to the north, the much larger and different types of alluvial systems (AS-1 and AS-2 in Fig. 13; Fig. 15 A and B) suggest that the drainage area in the footwall of that fault must have much greater extent (Fig. 15A), and in this case the fluvial catchment could extend outside of the semiarid climate zone extending farther north in a more humid climate zone possibly corresponding to a relatively high area under the influence of moist Atlantic winds from the Basque - Cantabrian Basin in the Boreal domain (Benito et al. 2005). Moreover, during the Stage 2, when a fluvial distributive fan system with braided channels developed in this halfgraben (AS-2 in Fig. 13; Fig. 15A), even an enlarged drainage area could occur, possibly favoring river capture with the fluvial fan system being fed perennially. Somewhat and to a lesser extent in the Western Cameros rift basins the situation could be similar to that described by Fordham et al. (2010) for the northern Basin and Range province, USA, where “perennial rivers linking multiple basins, and delivering significant sediment to the fill, are rare and restricted to streams with large, well-integrated catchments lying outside the dryland climatic zone”, and “discharge losses in the dryland zone cause such perennial streams to be confined mostly to the margins of the extensional province”.

Tectonics

As climate and source-area lithology can be considered constant factors, tectonics, together with the size of the source area, is addressed as the main factor controlling the stratigraphic, sedimentological, and paleogeographical differences above. In extensional, rift-related settings, tectonics controls the subsidence rate and footwall uplift, two factors that are directly related to the accommodation space in the hangingwall and sediment input coming from erosion of the footwall, respectively (Miall 1981, Davies et al. 2000, Schumm et al. 2000, Gupta and Cowie 2000, Gawthorpe and Leeder 2000). Therefore, differential tectonic activity between the fracture controlling the northern Vizcaínos halfgraben basin and those controlling the other halfgraben basins can explain the stratigraphic and sedimentological differences between them.

The coexistence of two different types of halfgraben basins in the study area with different alluvial systems indicates the different behavior of each extensional structure regarding the tectonic uplift and subsidence rate. The thickness of the sedimentary record and the fan size have been related to the size and weathering magnitude in the drainage areas (Denny 1967, Leeder 1999) and can, in turn, be related to the intensity of tectonic uplift (Nilsen 1969). Thus, differential tectonic uplift can be inferred for the structure controlling the alluvial systems in the Vizcainos halfgraben basin (Fig. 15). The bigger alluvial system in this northernmost halfgraben basin implies a bigger drainage area and most likely also a greater tectonic uplift, which would have favored weathering and sediment input. Conversely, the dominant smaller and poorly channelized alluvial fan systems can be related to lesser tectonic uplift. However, the tectonic uplift must have been quite homogeneous for the halfgrabens faults related to these smaller and poorly channelized alluvial fans, as the facies and their thickness, mapped extent and the correlation imply similar sizes and types of transport. The differences in the lithology and the absence of debris flows in some of the basins of the South Sector were related, as previously discussed, to the different lithological composition of the drainage areas in each system.

Conversely, the stratigraphic architecture of the sedimentary record in each halfgraben can be related to the subsidence rate and its relation to the sediment input. The dominant retrograding geometry of the alluvial record in the North Sector during Stage 1 (Fig. 10) indicates that sediment input, even in the Vizcaínos halfgraben, was not enough to exceed the generation of accommodation space, which suggests relatively high tectonic subsidence. The overstepping of the palustrine environments during Stage 2 also indicates that sediment input progressively decreased in this sector from the first to second stages (Figs. 10, 15), which suggests decreasing tectonic uplift. However, in the South Sector, the dominant prograding geometry of the Stage 1 indicates that sediment input was able to exceed the generation of accommodation space, which suggests a relatively low tectonic subsidence rate.

Notably, sedimentation was mainly carbonate lacustrine - palustrine during Stage 2 in the South Sector, and the depocenter migrated to the south, indicating a new tectonic control coming from the southernmost normal fault, which currently constitutes the South Cameros Thrust (Fig. 15). The thick sedimentary record of Stage 2 (lacustrine sedimentation) is interpreted as the result of more constant subsidence that was generated in smaller but more continuous pulses, which favored the vertical stacking of shallowing-upwards lacustrine - palustrine sequences. The absence of clastic sedimentation indicates that there was no significant sediment input, which implies low tectonic uplift and very likely the establishment of a footwall karstic drainage area.

Coexistence of Different Alluvial Systems and Depositional Architectures in the Same Paleogeographic Framework: Implications for the Use of Alluvial Basins as Tools to Interpret Early Extensional Settings

The heterogeneity displayed by the alluvial depositional systems in the earliest syn-rift sedimentary record of many rift basins is mainly a consequence of the differential tectonic activity expected for a stage of rift initiation and, consequently, of the correlative sizes of the drainage areas that are created (Cowie et al. 2000, Davies et al. 2000, Gawthorpe and Leeder 2000). In the West Cameros Basin, the main consequence of this tectonic heterogeneity during rift initiation is the coexistence, under similar climatic conditions and in the same paleogeographic area with similar, soft source-area lithologies, of several halfgraben basins displaying different alluvial systems: small poorly channelized alluvial fan systems, which are the norm (AS-3 in Figs. 13, 15A), and bigger, highly channelized alluvial fan and fluvial distributive fan systems, which are the exception in the Vizcaínos halfgraben basin (AS-1 and AS-2, respectively, in Figs. 13, 15A, 15B). Moreover, halfgraben basins display different alluvial depositional architectures. During the Stage 1 (Figs. 10, 15A), all of the halfgraben basins in the North Sector, which are controlled and bounded by normal faults and have footwall drainage areas to the north, display retrograding depositional architecture. However, all of the halfgraben basins in the South Sector except the AHE halfgraben, are controlled and bounded by normal faults, have footwall drainage areas to the south, and display prograding depositional architecture. The Arroyo del Helechal halfgraben basin displays a retrograding depositional architecture and is controlled and bounded by a normal fault to the north with a related footwall drainage area also to the north.

This coexistence of different alluvial systems and depositional architectures in the same paleogeographic framework has important implications when using the sedimentary record of alluvial halfgraben basins from the early stages of rifting to make climatic and tectonic interpretations, as changes in the dominant sedimentary process or architecture in this type of basins as indicators of significant climate changes (Harvey et al., 2005, Dorn, 2009). However, the analysis of the study area shows how fault activity during the earliest stages of a rift system can generate high degrees of sedimentary heterogeneity and how this heterogeneity is recorded by the alluvial systems in the form of differences in their facies associations and architectures. There are several main factors that must be taken into account when studying the controls on sedimentation in this type of tectonic setting: tectonic activity (Davies et al. 2000, Schumm et al. 2000, Gupta and Cowie 2000, Gawthorpe and Leeder 2000) and catchment characteristics (Blair and McPherson 1994a and 1994b, Nichols and Thompson 2005, Lambiase and Morley 1999, Viseras et al. 2003, Fordham et al. 2010), i.e., from the fossil record, inferred size, lithology, and climate of drainage areas, which directly control their types of transport, depositional arrangement, the size and even the type of the alluvial systems, and the subsidence rate, which controls their stratigraphy. In a tectonic setting related to the earliest stages of a rift system, these factors can vary significantly, as proven by the study area in this work: e.g., tectonic uplift and catchment sizes can vary from one structure to another even within the same paleogeographic sector, and the subsidence rate can vary greatly between different paleogeographic sectors, which is probably due to the orientation of the faults. Other factors related to tectonics, such as the dips of the fault and the orientation of the system must also be taken into account, as they influence the location of the source area and can have specific consequences in the sedimentary architecture.

CONCLUSIONS

The detailed stratigraphic, sedimentological, and paleoenvironmental analysis of the earliest syn-rift sedimentary record of the West Cameros Basin has confirmed that sedimentation took place in different alluvial halfgraben basins. Two paleogeographic sectors were distinguished based on stratigraphic and sedimentological differences: a North Sector characterized by S-oriented and sedimentologically heterogeneous alluvial systems and a retrograding depositional geometry; and a South Sector characterized by dominantly N-oriented and sedimentologically homogeneous alluvial systems and a predominantly prograding depositional geometry. In addition, two different paleogeographic stages have been distinguished: one during which sedimentation was mostly alluvial (Stage 1), and one during which lacustrine sedimentation extended (Stage 2) except for some specific halfgrabens.

Based on facies analysis and correlation and the inferred sedimentary architecture, three types of alluvial systems can be distinguished in the halfgraben basins of the study area: 1) highly channelized alluvial fan system; 2) fluvial distributive fan system (braided channels) changing downstream to an axial tributary fluvial system (braided river); and 3) poorly channelized alluvial fan systems.

As climate and the source area lithology can be considered constant factors, tectonics and catchment sizes are addressed as the main factors that control the stratigraphic, sedimentological, and paleogeographical differences described. The coexistence of different halfgraben with different alluvial architectures indicates the different behavior of each extensional structure in terms of tectonic uplift and subsidence rate. Tectonic uplift was variable even among the structures of the same paleogeographic sector; the subsidence rate was more homogeneous within each sector, but variable among them. Catchment size should also be a very important control on the halfgraben basin-fill records. Thus, the drainage areas of the small and poorly channelized alluvial fan systems had to be very small; however, the drainage areas of the highly channelized alluvial fan and the fluvial distributive fan system with braided channels that developed during the paleogeographic stages 1 and 2, respectively, must have been much more extensive.

This has important implications in regard to using the sedimentary record of alluvial halfgraben basins to make climatic and tectonic interpretations, as changes in the dominant sedimentary processes and architectures in alluvial basins have been often used as indicators of significant climate changes. However, the analysis of the study area shows how fault activity and drainage-area sizes during the earliest stages of a rift system can generate high degrees of heterogeneity in alluvial-basin architecture and how this heterogeneity is recorded by the alluvial systems in the form of differences in their facies association and architecture. Therefore, this work concludes that both tectonics and catchment sizes exerted primary control on the sedimentary characteristics of the associated alluvial systems in the basins in this type of extensional setting, and care must be taken when making climatic and tectonic interpretations using the sedimentary record of these alluvial systems. Assessing the specific role of the different factors that control sedimentation in alluvial systems is often difficult, but the difficulty is higher for these earliest syn-rift stages and can lead to misinterpretation if the consequences of the different behaviors of each extensional structure and its footwall drainage area are not taken into account.

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FIGURE CAPTIONS

Figure 1: A) Geological setting of Cameros Basin (modified from Mas et al. 2002, 2003) with location of geological cross sections of Part B and the studied sector of Part C. B) Geological cross sections through the Cameros Basin (1 - 1´, 2 - 2´ and 3 - 3´) (modified from Guimerà et al., 1995, and Mas et al., 2003). C) Location of the twenty-eight stratigraphic sections studied for this work (modified from Mas et al. 2002, 2003): Torrelara (TO), Paules (PA), Aceña (AC), Morrión (MO), Rupelo (RU), San Millán (SM), Cubillejo (CU), Quintanilla (QU), Campolara (CA), Hortigüela (HO), Vizcainos (VZ), Jaramillo Quemado (JQ), Pinilla de los Moros (PM), Castrovido (CTV), Terrazas 2 (TR2), Terrazas 1 (TR1), Moncalvillo (MN), Arroyo del Helechal (AHE), Mamolar Norte (MAN), Mamolar Sur (MAS), Pinilla de los Barruecos (PI), La Gallega Sur (GAS), Talveila (TAL), Doña Santos (DS), Camino Forestal (CF), Área Recreativa (AR), Brezales (BR) and Espejón (ES).

Figure 2: A) General stratigraphic record of the Cameros Basin (modified from Mas et al. 2004, 2011); DS, depositional sequences (1 - 8). B) Stratigraphic framework of the studied sedimentary record at W Cameros Basin (modified from Arribas et al. 2003). In both figures the red rectangle indicates the studied depositional sequence DS1. Two different stages in the evolution of DS1 are also indicated.

Figure 3: Thickness distribution and general correlation of the main sections of each halfgraben basin. A) halfgraben structures from the North Sector; B) thickness distribution of the Brezales Fm, North Sector isopach curves in 20 m increments, Central and South Sectors isopach curves in 10 m increments; C) thickness distribution

of the Boleras Fm, North and Central Sectors isopach curves in 10 m increments, South Sector - isopach curves in 20 m increments; and D) halfgraben structures from the S Sector. Two different stages in the evolution of DS1 are also indicated.

Figure 4: Four representative stratigraphic sections (of the twenty-eight studied) of the facies recorded in the N Sector: Rupelo section (116 m), Rupelo Halfgraben; Jaramillo-Quemado section (100 m), Jaramillo Halfgraben; Vizcainos section (222 m), Vizcainos Halfgraben; and Terrazas 2 section (95 m), Vizcainos Halfgraben.

Figure 5: Four representative stratigraphic sections (of the twenty-eight studied) of the facies recorded in the S Sector: Arroyo del Helechal section (76 m), Helechal Halfgraben; Mamolar Norte section (56 m), Mamolar Halfgraben; Brezales section (86 m), Brezales Halfgraben; Camino Forestal section (107 m), Huerta del Rey Halfgraben.

Figure 6: Paleocurrents for Brezales Fm in seven representative stratigraphic sections in the study area (see Figures 4 and 5): Rupelo section; Jaramillo-Quemado section; Vizcainos section; Terrazas 2 section; Arroyo del Helechal section; Mamolar Norte section; and Brezales section.

Figure 7: Thickness distribution and paleocurrent data in the Brezales Fm from various studied sections. See the stratigraphic position of Stages 1 and 2 in Fig. 8.

Figure 8: Architectural elements and facies associations (FA) distinguished in the study area. The letters in FA refer to the lithofacies described in Table 1. The lateral scale is in meters.

Figure 9: Calculated percentages of the clastic architectural elements (Fig. 8) and their correspondence with Facies Associations (FA) for each representative stratigraphic section shown in Figures 4 and 5.

Figure 10: Stratigraphic correlation of the stratigraphic sections based on mapping and the facies association distribution (location of each section in Fig. 1; some of them are detailed in Fig. 4 and Fig. 5).

Figure 11: Field examples of facies and facies associations. **A**) Planar and trough cross-bedded gravels (Gp and Gt as GB in CH), Vizcaínos section (FA-1, scale = 1 m). B) Cross-bedded gravels displaying lateral accretion in a small paleochannel (Gt with LA in CH) that is sandwiched in red mudstone (Fmr as FF), Vizcaínos section (FA-2, marker = 13 cm). C) Large-scale planar-cross-bedded gravels with secondary trough cross-bedding (Gp and Gt as GB in CH), Terrazas 2 section (FA-3, scale = 60 cm). D) Matrix-supported massive gravel debris flow (Gmm in SG) with boulders (D.1), Quintanilla section (FA-4) and the detail of the matrix-supported framework (D.2), Rupelo section (FA-4, hammer = 32 cm). E) Mass-flow deposit (Gmm as SG; Fig 7) showing the polymictic composition of these deposits in the South Sector: carbonate rock fragments (red arrow), clastic sedimentary rock fragments (white arrow), and quartz clasts (yellow arrow), Arroyo del Helechal section (FA-4). F) Thick sheet-shaped flat-bedded sandstone (Sh as SB) overlain by lobe-shaped matrix-supported massive gravel (paraconglomerate; Gmm as SG) displaying a laminar calcrete (P) that developed on top, Arroyo del Helechal section (FA-4, scale = 1. 20 m).

Figure 12: Field and microscope examples of facies and facies associations. A) Massive and planar cross-bedded tabular gravel deposit (Gcm and Gp as GB), Brezales section (FA-5, hammer = 32 cm). B) Flat-bedded sandstone (Sh as SB) overlain by a thick calcrete (P) that shows nodular, laminar, and brecciated - pisolitic structures from bottom to top, and a conglomerate bed lying on top (Gcm as GB), Mamolar Norte section (FA-5, hammer = 32 cm). C) Calcrete deposit (P corresponding to PC) that developed on red sandy siliciclastic mudstones (Fmr in FF), Rupelo section (FA-6, notebook = 19 cm). D) Coarse sandy trough cross-bedded deposit (pebbly coarse to coarse sandstone; St as SB) eroding a previous calcrete deposit (P), Brezales section (FA-6, hammer = 32 cm). E) Transmitted-light microscope image of a bioclastic packstone with charophytes (well-bedded limestone; Lb as SLC), Brezales section (FA-7). F) Transition between calcrete deposits developed on marl and marly siliciclastic mudstone (P and Mr, respectively, in MF) to massive and nodular (Ln) limestones (Lm and Ln, respectively, in CTB), Paules section, (FA-7, scale = 1 m).

Figure 13: Recognized types of alluvial systems: AS-1, highly channelized alluvial fan system (Stage 1 in the Vizcaínos halfgraben); AS-2, fluvial distributive fan system (braided channels) changing downstream to an axial tributary fluvial system (braided river) (Stage 2 in the Vizcaínos halfgraben); and AS-3, poorly channelized alluvial fan system (Stage 1 in all other halfgrabens).

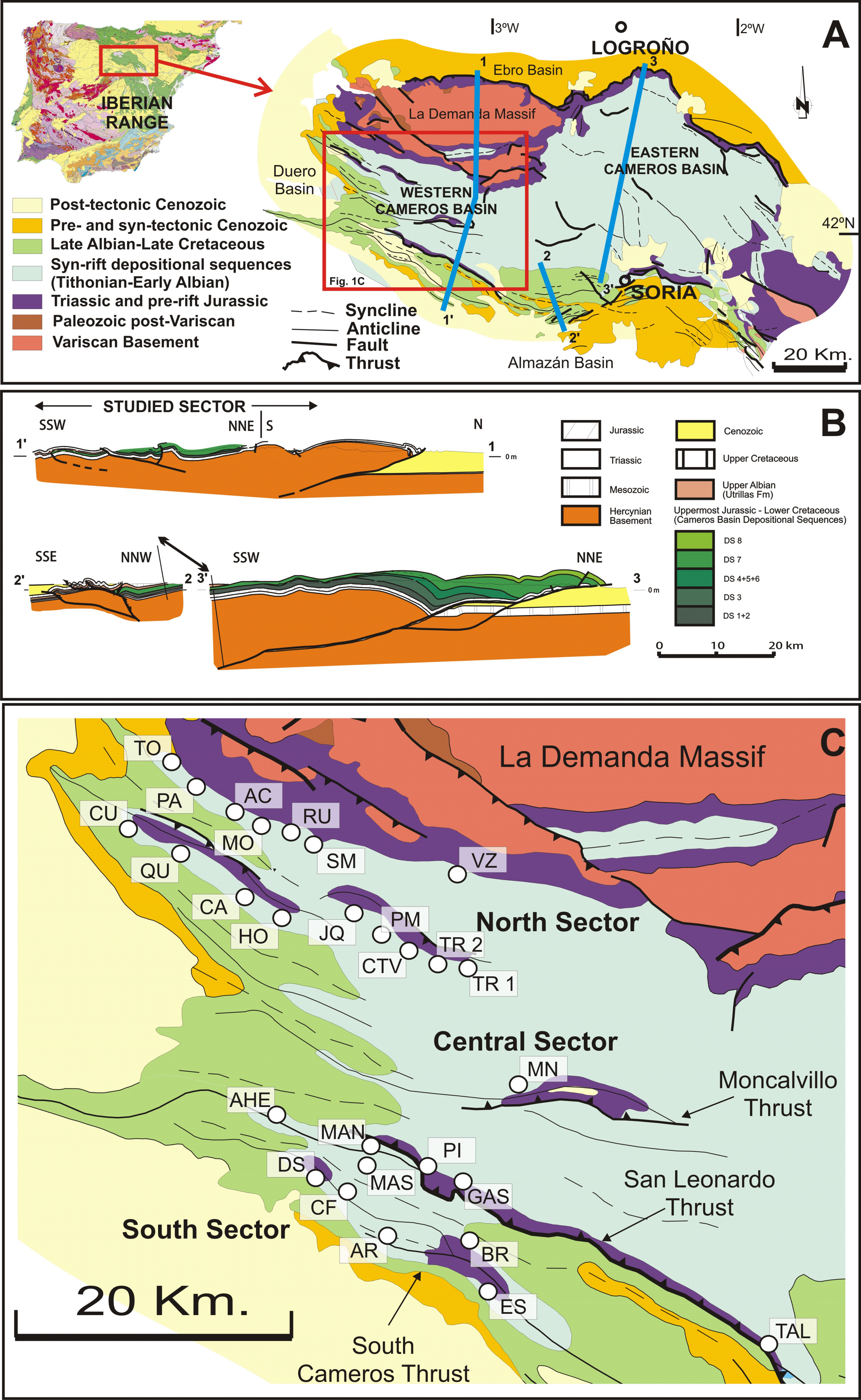
Figure 14: A) calculated percentages of the clastic architectural elements (Fig. 8) for each type of distinguished alluvial system; B) calculated percentages of the facies associations (FA) for each type of distinguished alluvial system.

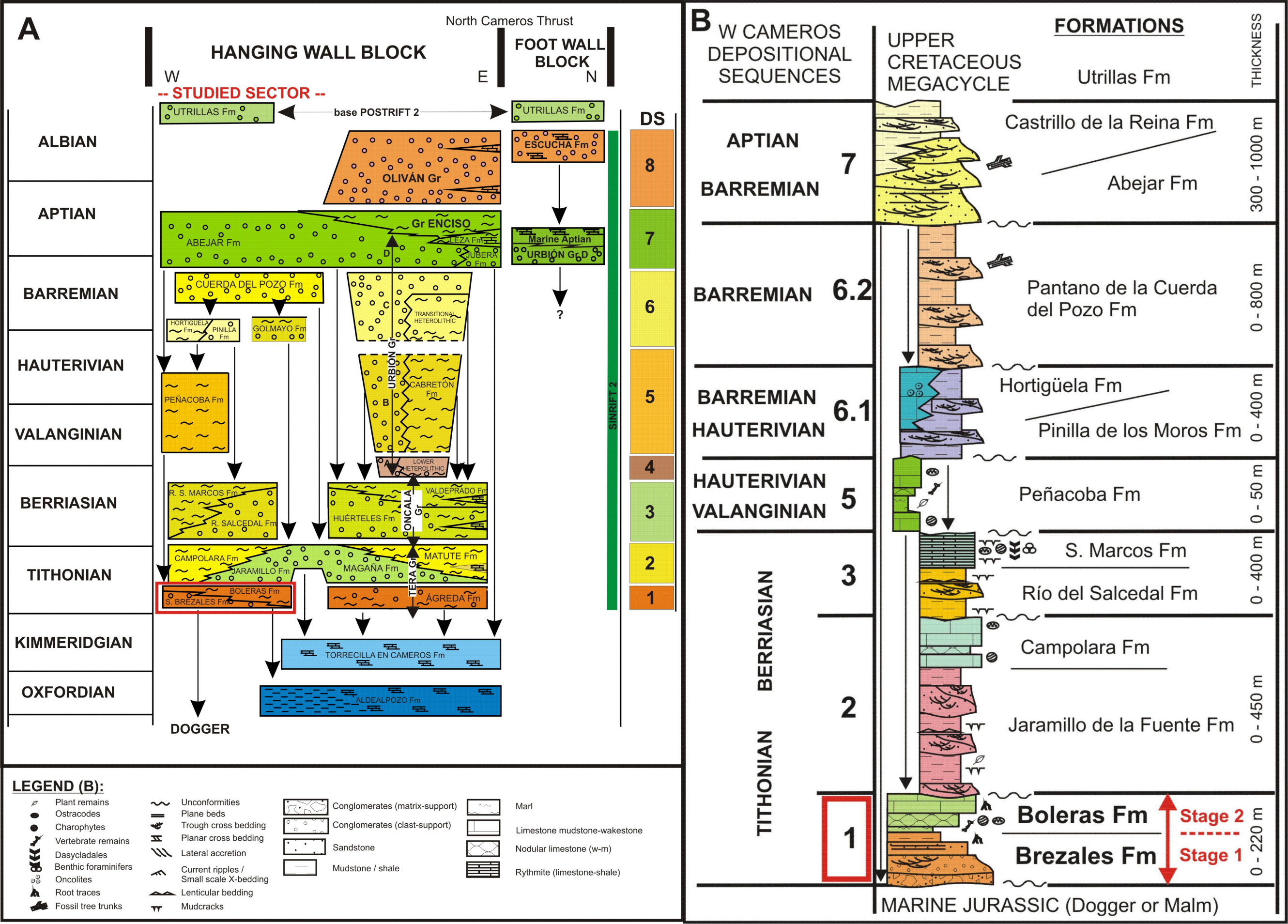
Figure 15: Environmental paleogeographic distribution and evolution of the study area during the earliest syn-rift stages. A) Schematic paleogeography during Stage 1. B) Schematic paleogeography during Stage 2.

Table 1: Lithofacies (clastic facies code follows Miall, 2010).

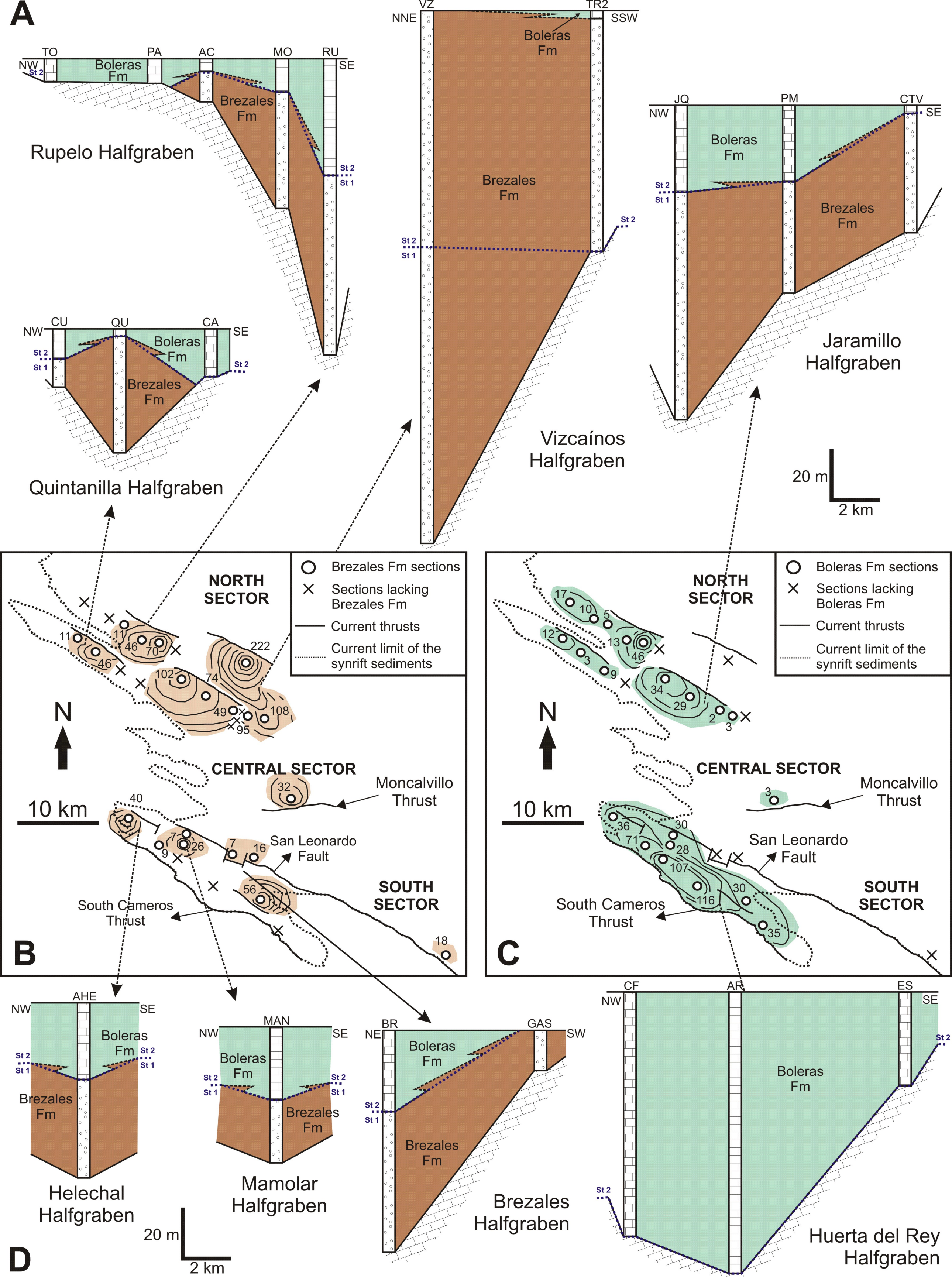
Table 1. Lithofacies (clastic facies code follows Miall, 2010).

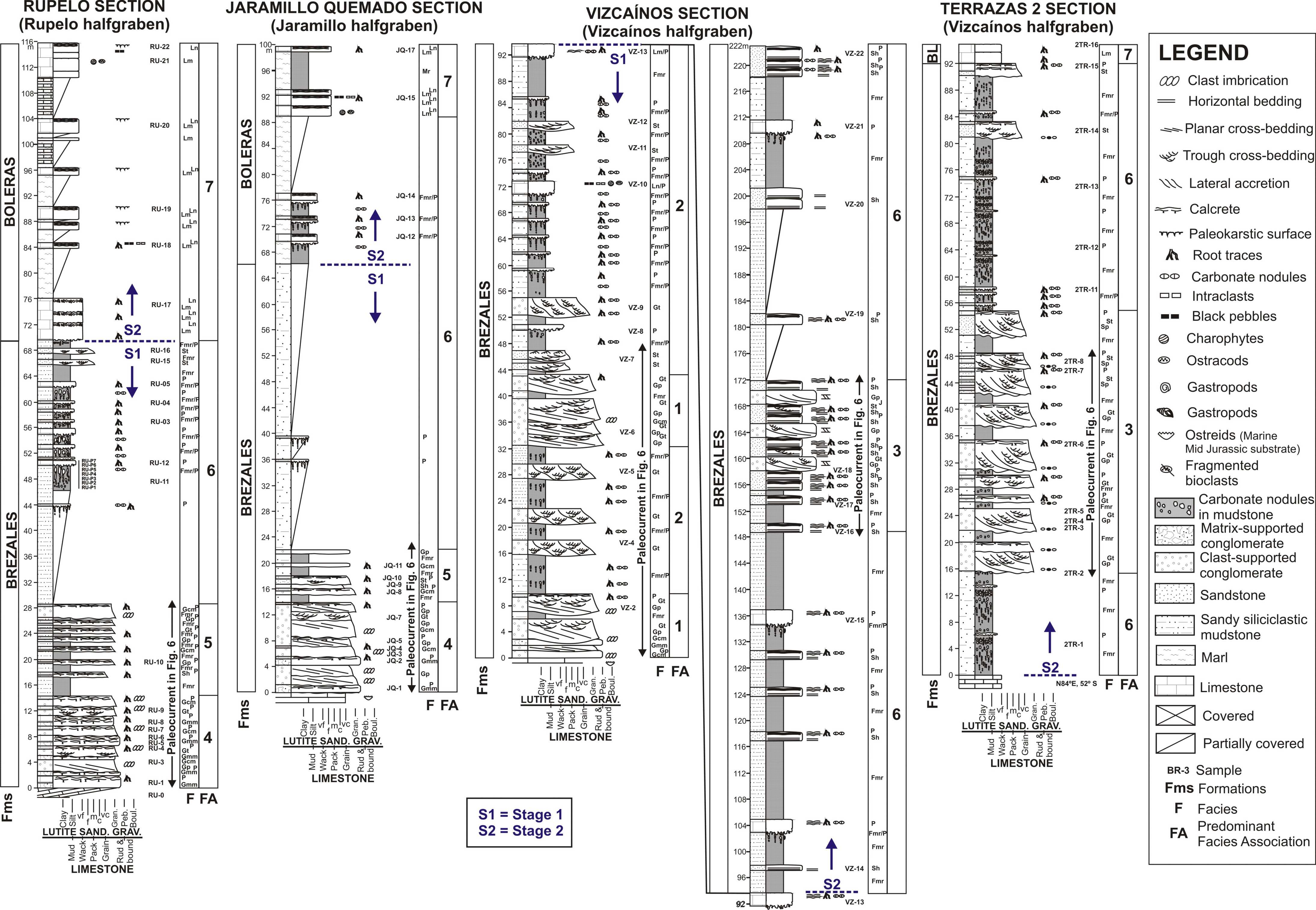
Clastic lithofacies			
Facies code	**Lithofacies**	**Sedimentary structures or textural organization**	**Interpretation**
Gmm	matrix-supported massive gravel (paraconglomerate)	weak grading	plastic debris flow (high-strengh, viscous)
Gmg	matrix-supported gravel (paraconglomerate)	Inverse to normal grading	pseudoplastic debris flow (low-strengh, viscous)
Gcm	clast-supported massive gravel (orthoconglomerate)	pebbles imbrication	pseudoplastic debris flow (inertial bedload, turbulent flow)
Gt	gravel (orthoconglomerate), stratified	trough crossbeds	sinuous-crested and linguoid (3-D) dunes, minor channel fills
Gp	gravel (orthoconglomerate), stratified	planar crossbeds	transverse bedforms (2-D dunes)
St	sandstone, fine to v. coarse, may be pebbly	solitary or grouped trough crossbeds	sinuous-crested and linguoid (3-D) dunes
Sh	sandstone, v. fine to coarse, may be pebbly	horizontal lamination parting or streaming lineation	plane-bed flow (super-critical flow)
Fmr	mudstone, siltstone; occasionally fine to v. fine sandstone thin layers intercalated	massive, desiccation cracks, roots, bioturbation; occasionally ripple cross-laminated thin layers intercalated	overbank, root bed, incipient soil; occasionally ripples (lower flow regime)
Carbonate and mixed carbonate-siliciclastic lithofacies			
Facies code	**Lithofacies**	**Sedimentary estructures, textures and microfabrics**	**Interpretation**
Lb	well-bedded limestone, charophytes (girogonites and talus), ostracods, gastropods, bivalves	wackestone, packstone; unfragmented microfossils; no pedogenic features	carbonate sedimentation in a shallow lacustrine quite environment
Lm	massive limestone, scarce charophytes, ostracods, gastropods	mudstone, wackestone; subaerial exposure, especially desiccation	carbonate sedimentation in a very shallow lacustrine quite environment
Ln	nodular limestone, scarce charophytes, ostracods, gastropods	original textures rarely preserved, intense pedogenic modification (desiccated, brecciated and nodular microfabrics)	carbonate sedimentation in a shallow lacustrine environment subject to periodical desiccation and pedogenesis
Mr	massive marl and muddy limestone	marl and marly mudstone, fines siliciclastic and muddy carbonate	fine carbonate-siliciclastic sedimentation in peri-lacustrine palustrine environments; moderate to intense pedogenic features
P	paleosol carbonate (pedogenic calcrete)	pedogenic microfabric and features: filaments, mootling, desiccation, nodules, lamination, brecciation, pseudomicrokarst cavities, pedotubules, rhizocretions	pedogenic secondary carbonate displacive precipitation


A
IBERIAN RANGE
3ºW
2ºW
LOGROÑO
Ebro Basin
La Demanda Massif
Duero Basin
WESTERN CAMEROS BASIN
EASTERN CAMEROS BASIN
42ºN
SORIA
Almazán Basin
Fig. 1C
20 Km.
Post-tectonic Cenozoic
Pre- and syn-tectonic Cenozoic
Late Albian-Late Cretaceous
Syn-rift depositional sequences (Tithonian-Early Albian)
Triassic and pre-rift Jurassic
Paleozoic post-Variscan
Variscan Basement
Syncline
Anticline
Fault
Thrust
B
STUDIED SECTOR
SSW
NNE
S
N
1'
1
SSE
NNW
2'
2
3'
SSW
NNE
3
0 m
Jurassic
Triassic
Mesozoic
Hercynian Basement
Cenozoic
Upper Cretaceous
Upper Albian (Utrillas Fm)
Uppermost Jurassic - Lower Cretaceous (Cameros Basin Depositional Sequences)
DS 8
DS 7
DS 4+5+6
DS 3
DS 1+2
0
10
20 km
C
La Demanda Massif
TO
PA
CU
AC
RU
MO
QU
SM
VZ
CA
HO
JQ
PM
TR 2
CTV
TR 1
North Sector
Central Sector
MN
Moncalvillo Thrust
AHE
MAN
PI
DS
MAS
GAS
CF
San Leonardo Thrust
South Sector
AR
BR
ES
20 Km.
South Cameros Thrust
TAL

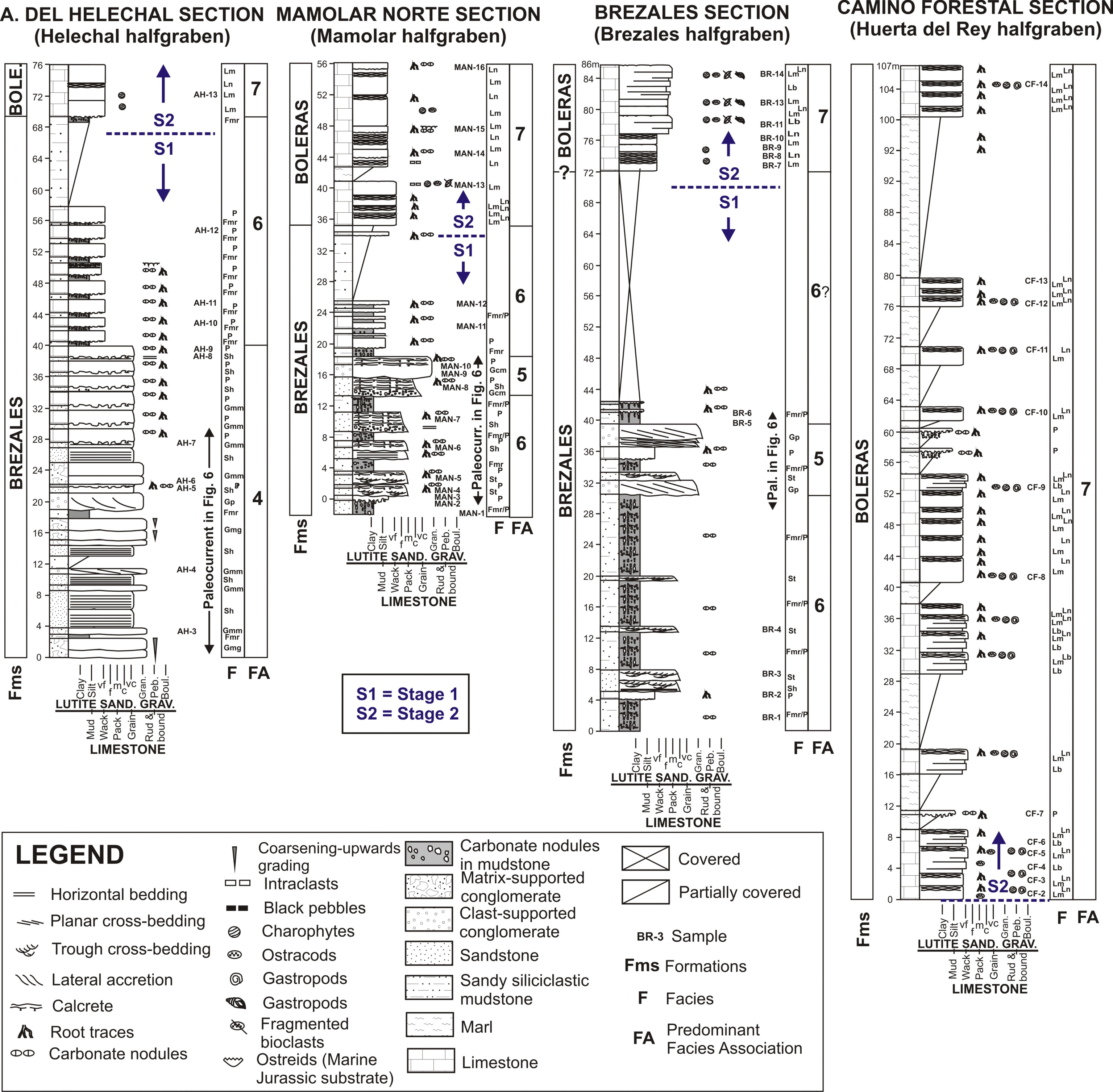


A
North Cameros Thrust
HANGING WALL BLOCK
FOOT WALL BLOCK
W
E
N
-- STUDIED SECTOR --
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
TITHONIAN
KIMMERIDGIAN
OXFORDIAN
UTRILLAS Fm
base POSTRIFT 2
ESCUCHA Fm
OLIVÁN Gr
Gr ENCISO
ABEJAR Fm
LEZA Fm
JUBERA Fm
Marine Aptian
URBIÓN Gr D
CUERDA DEL POZO Fm
HORTIGÜELA Fm
PINILLA Fm
GOLMAYO Fm
TRANSITIONAL HETEROLITHIC
URBIÓN Gr
CABRETÓN Fm
PEÑACOBA Fm
LOWER HETEROLITHIC
R. S. MARCOS Fm
R. SALCEDAL Fm
HUÉRTELES Fm
ONCALA Gr
VALDEPRADO Fm
CAMPOLARA Fm
JARAMILLO Fm
MAGAÑA Fm
MATUTE Fm
TERA Gr
BOLERAS Fm
S. BREZALES Fm
ÁGREDA Fm
TORRECILLA EN CAMEROS Fm
ALDEALPOZO Fm
DOGGER
SINRIFT 2
DS
8
7
6
5
4
3
2
1
B
W CAMEROS DEPOSITIONAL SEQUENCES
UPPER CRETACEOUS MEGACYCLE
FORMATIONS
THICKNESS
Utrillas Fm
APTIAN
BARREMIAN
7
Castrillo de la Reina Fm
Abejar Fm
300 - 1000 m
BARREMIAN
6.2
Pantano de la Cuerda del Pozo Fm
0 - 800 m
BARREMIAN
HAUTERIVIAN
6.1
Hortigüela Fm
Pinilla de los Moros Fm
0 - 400 m
HAUTERIVIAN
VALANGINIAN
5
Peñacoba Fm
0 - 50 m
BERRIASIAN
3
S. Marcos Fm
Río del Salcedal Fm
0 - 400 m
2
Campolara Fm
Jaramillo de la Fuente Fm
0 - 450 m
TITHONIAN
1
Boleras Fm
Brezales Fm
Stage 2
Stage 1
0 - 220 m
MARINE JURASSIC (Dogger or Malm)
LEGEND (B):
Plant remains
Ostracodes
Charophytes
Vertebrate remains
Dasycladales
Benthic foraminifers
Oncolites
Root traces
Fossil tree trunks
Unconformities
Plane beds
Trough cross bedding
Planar cross bedding
Lateral accretion
Current ripples / Small scale X-bedding
Lenticular bedding
Mudcracks
Conglomerates (matrix-support)
Conglomerates (clast-support)
Sandstone
Mudstone / shale
Marl
Limestone mudstone-wakestone
Nodular limestone (w-m)
Rythmite (limestone-shale)

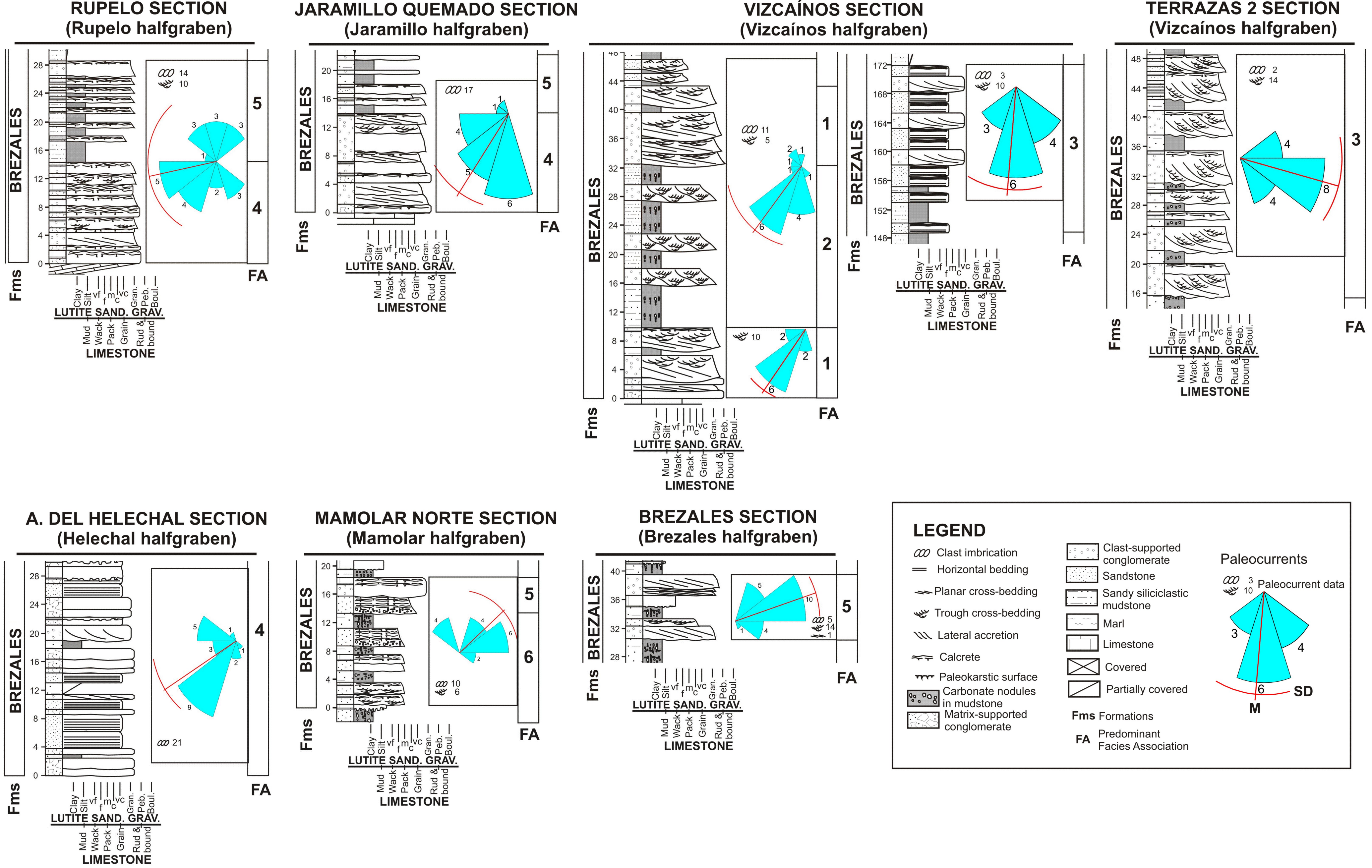

A
Rupelo Halfgraben
TO
PA
AC
MO
RU
NW
SE
Boleras Fm
Brezales Fm
St 2
St 1
Quintanilla Halfgraben
CU
QU
CA
Vizcaínos Halfgraben
VZ
TR2
NNE
SSW
Jaramillo Halfgraben
JQ
PM
CTV
20 m
2 km
B
NORTH SECTOR
CENTRAL SECTOR
SOUTH SECTOR
Brezales Fm sections
Sections lacking Brezales Fm
Current thrusts
Current limit of the synrift sediments
Moncalvillo Thrust
San Leonardo Fault
South Cameros Thrust
10 km
N
C
Boleras Fm sections
Sections lacking Boleras Fm
D
Helechal Halfgraben
AHE
Mamolar Halfgraben
MAN
Brezales Halfgraben
BR
GAS
NE
SW
Huerta del Rey Halfgraben
CF
AR
ES



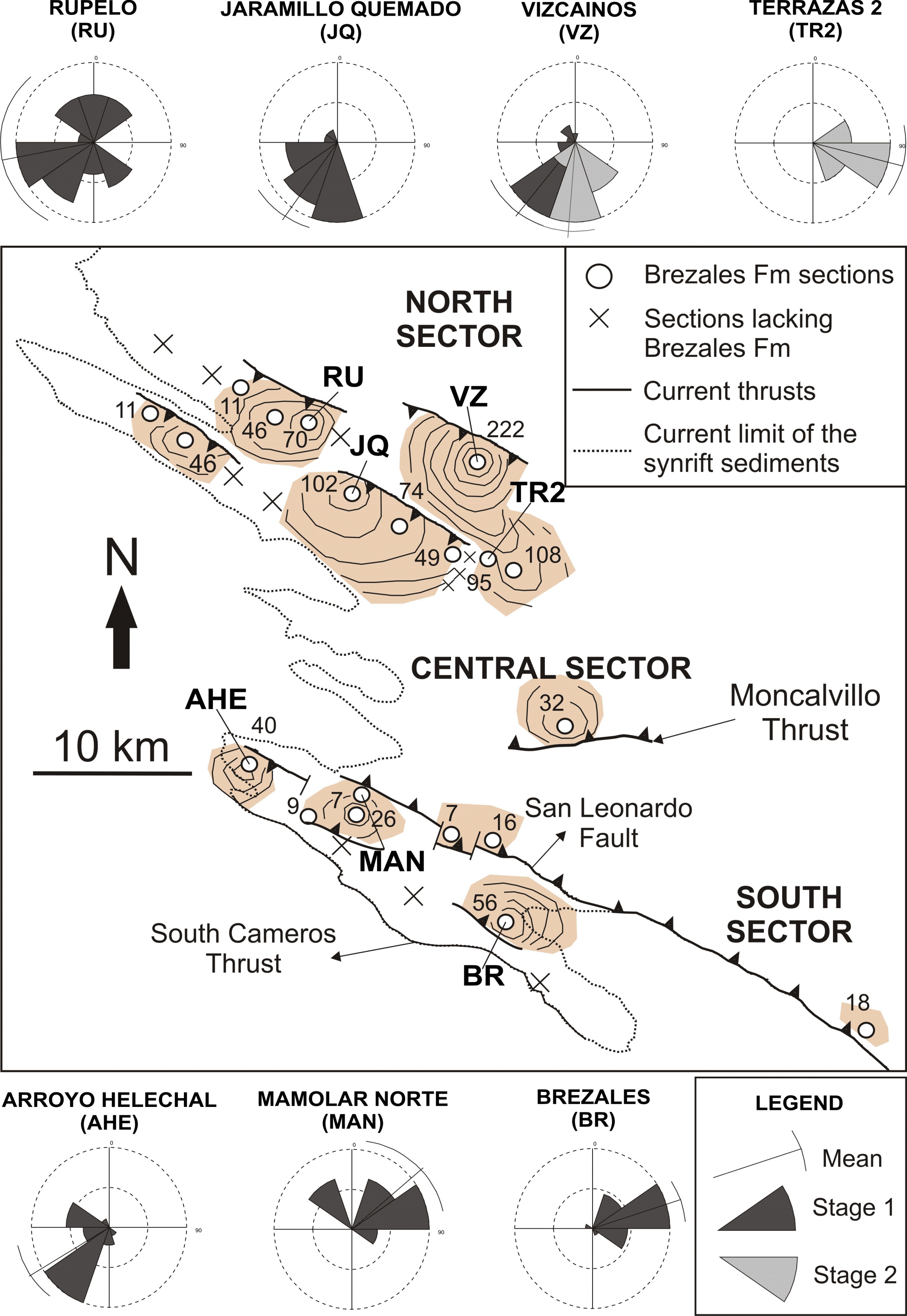
RUPELO SECTION
(Rupelo halfgraben)
JARAMILLO QUEMADO SECTION
(Jaramillo halfgraben)
VIZCAÍNOS SECTION
(Vizcaínos halfgraben)
TERRAZAS 2 SECTION
(Vizcaínos halfgraben)
BOLERAS
BREZALES
BL
Paleocurrent in Fig. 6
S1
S2
S1 = Stage 1
S2 = Stage 2
Fms
F
FA
LUTITE SAND. GRAV.
Clay
Silt
vf
f
m
c
vc
Gran.
Peb.
Boul.
Mud
Wack
Pack
Grain
Rud & bound
LIMESTONE
N84°E, 52° S
LEGEND
Clast imbrication
Horizontal bedding
Planar cross-bedding
Trough cross-bedding
Lateral accretion
Calcrete
Paleokarstic surface
Root traces
Carbonate nodules
Intraclasts
Black pebbles
Charophytes
Ostracods
Gastropods
Gastropods
Ostreids (Marine Mid Jurassic substrate)
Fragmented bioclasts
Carbonate nodules in mudstone
Matrix-supported conglomerate
Clast-supported conglomerate
Sandstone
Sandy siliciclastic mudstone
Marl
Limestone
Covered
Partially covered
BR-3 Sample
Fms Formations
F Facies
FA Predominant Facies Association



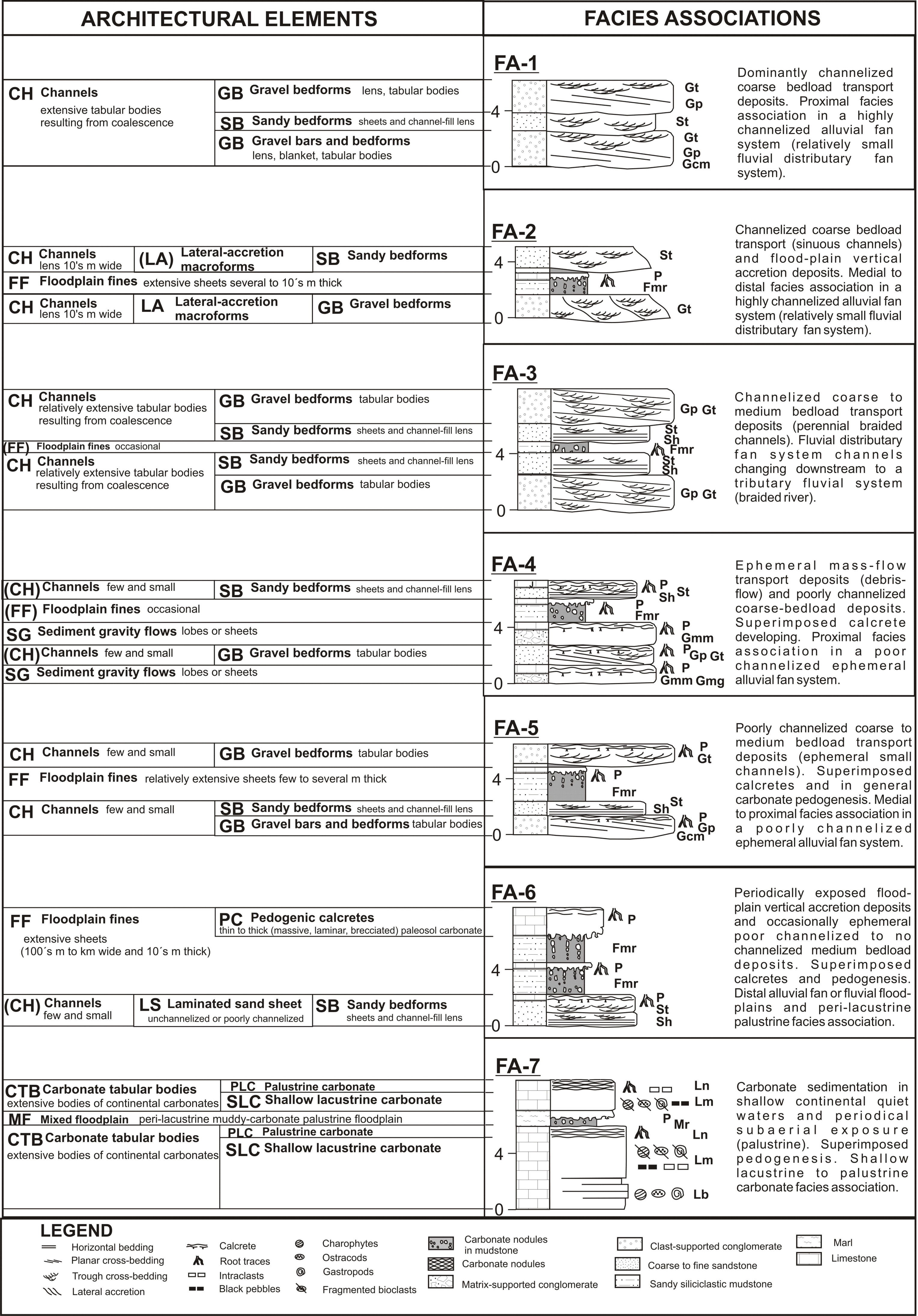
A. DEL HELECHAL SECTION
(Helechal halfgraben)
MAMOLAR NORTE SECTION
(Mamolar halfgraben)
BREZALES SECTION
(Brezales halfgraben)
CAMINO FORESTAL SECTION
(Huerta del Rey halfgraben)
BOLE.
BOLERAS
BREZALES
S1
S2
Paleocurrent in Fig. 6
Paleocurr. in Fig. 6
Pal. in Fig. 6
Fms
F
FA
LUTITE SAND. GRAV.
Clay Silt vf f m c vc Gran. Peb. Boul.
Mud Wack Pack Grain Rud & bound
LIMESTONE
S1 = Stage 1
S2 = Stage 2
LEGEND
Horizontal bedding
Planar cross-bedding
Trough cross-bedding
Lateral accretion
Calcrete
Root traces
Carbonate nodules
Coarsening-upwards grading
Intraclasts
Black pebbles
Charophytes
Ostracods
Gastropods
Gastropods
Fragmented bioclasts
Ostreids (Marine Jurassic substrate)
Carbonate nodules in mudstone
Matrix-supported conglomerate
Clast-supported conglomerate
Sandstone
Sandy siliciclastic mudstone
Marl
Limestone
Covered
Partially covered
BR-3 Sample
Fms Formations
F Facies
FA Predominant Facies Association



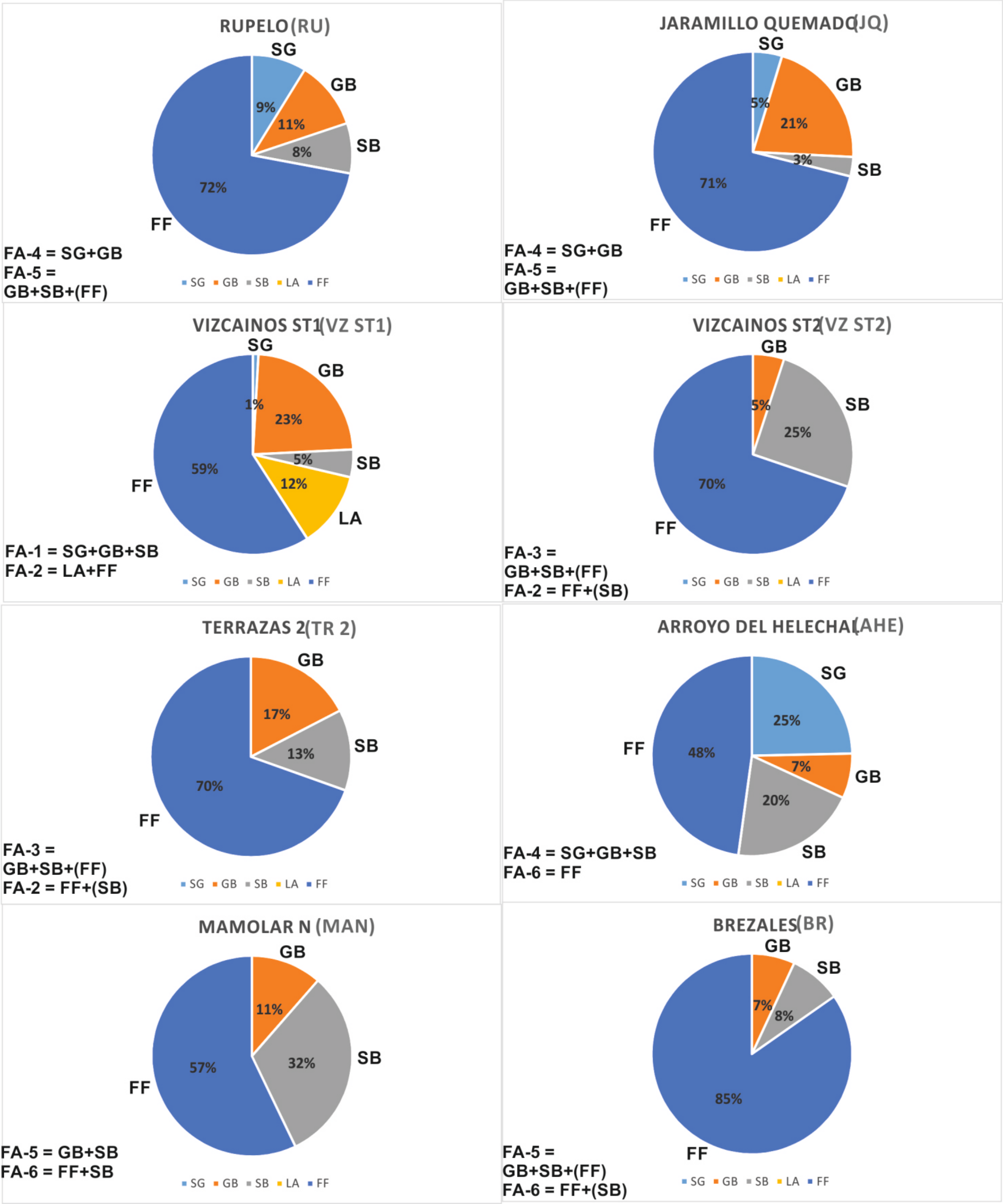
RUPELO SECTION
(Rupelo halfgraben)
JARAMILLO QUEMADO SECTION
(Jaramillo halfgraben)
VIZCAÍNOS SECTION
(Vizcaínos halfgraben)
TERRAZAS 2 SECTION
(Vizcaínos halfgraben)
A. DEL HELECHAL SECTION
(Helechal halfgraben)
MAMOLAR NORTE SECTION
(Mamolar halfgraben)
BREZALES SECTION
(Brezales halfgraben)
BREZALES
Fms
FA
Clay
Silt
vf
f
m
c
vc
Gran.
Peb.
Boul.
LUTITE SAND. GRAV.
Mud
Wack
Pack
Grain
Rud & bound
LIMESTONE
LEGEND
Clast imbrication
Horizontal bedding
Planar cross-bedding
Trough cross-bedding
Lateral accretion
Calcrete
Paleokarstic surface
Carbonate nodules in mudstone
Matrix-supported conglomerate
Clast-supported conglomerate
Sandstone
Sandy siliciclastic mudstone
Marl
Limestone
Covered
Partially covered
Fms Formations
FA Predominant Facies Association
Paleocurrents
Paleocurrent data
SD
M

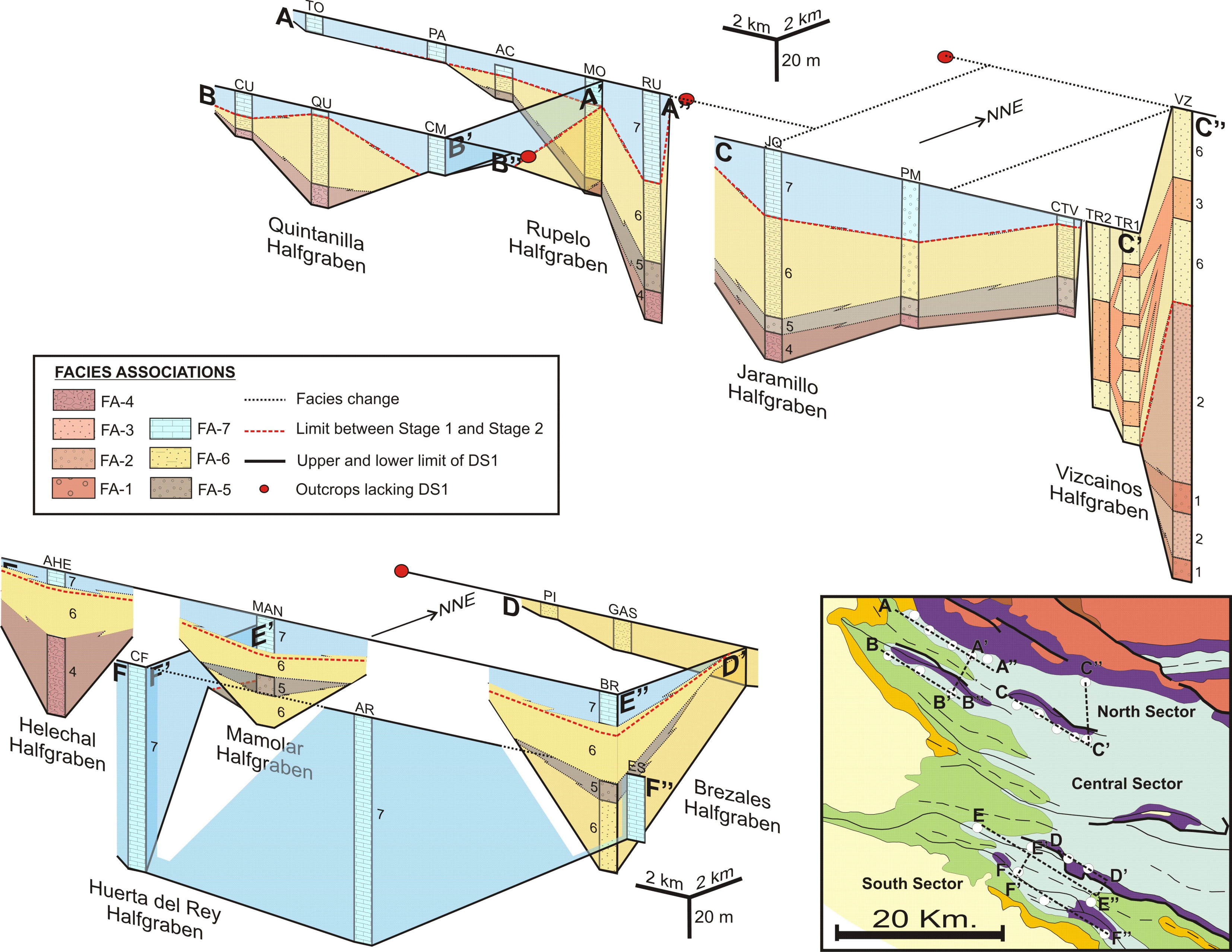


RUPELO (RU)
JARAMILLO QUEMADO (JQ)
VIZCAINOS (VZ)
TERRAZAS 2 (TR2)
Brezales Fm sections
Sections lacking Brezales Fm
Current thrusts
Current limit of the synrift sediments
NORTH SECTOR
RU
VZ
JQ
TR2
11
11
46
46
70
102
74
222
49
95
108
N
CENTRAL SECTOR
32
Moncalvillo Thrust
AHE
40
10 km
9
7
26
7
16
MAN
San Leonardo Fault
56
SOUTH SECTOR
South Cameros Thrust
BR
18
ARROYO HELECHAL (AHE)
MAMOLAR NORTE (MAN)
BREZALES (BR)
LEGEND
Mean
Stage 1
Stage 2

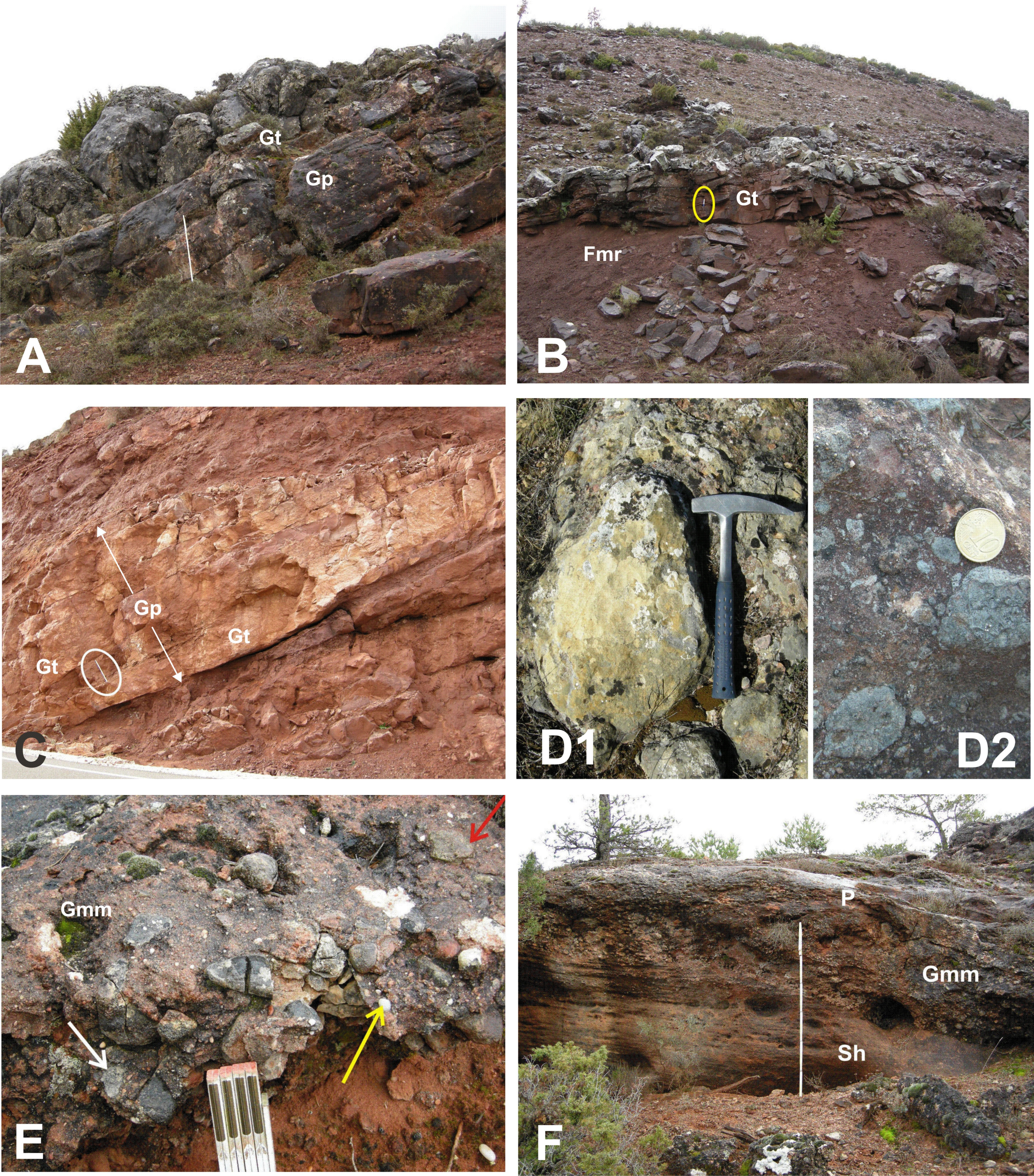


ARCHITECTURAL ELEMENTS
FACIES ASSOCIATIONS
FA-1
CH Channels extensive tabular bodies resulting from coalescence
GB Gravel bedforms lens, tabular bodies
SB Sandy bedforms sheets and channel-fill lens
GB Gravel bars and bedforms lens, blanket, tabular bodies
Gt Gp St Gt Gp Gcm
4
0
Dominantly channelized coarse bedload transport deposits. Proximal facies association in a highly channelized alluvial fan system (relatively small fluvial distributary fan system).
FA-2
CH Channels lens 10's m wide
(LA) Lateral-accretion macroforms
SB Sandy bedforms
FF Floodplain fines extensive sheets several to 10´s m thick
CH Channels lens 10's m wide
LA Lateral-accretion macroforms
GB Gravel bedforms
St P Fmr Gt
4
0
Channelized coarse bedload transport (sinuous channels) and flood-plain vertical accretion deposits. Medial to distal facies association in a highly channelized alluvial fan system (relatively small fluvial distributary fan system).
FA-3
CH Channels relatively extensive tabular bodies resulting from coalescence
GB Gravel bedforms tabular bodies
SB Sandy bedforms sheets and channel-fill lens
(FF) Floodplain fines occasional
CH Channels relatively extensive tabular bodies resulting from coalescence
SB Sandy bedforms sheets and channel-fill lens
GB Gravel bedforms tabular bodies
Gp Gt St Sh Fmr St Sh Gp Gt
4
0
Channelized coarse to medium bedload transport deposits (perennial braided channels). Fluvial distributary fan system channels changing downstream to a tributary fluvial system (braided river).
FA-4
(CH) Channels few and small
SB Sandy bedforms sheets and channel-fill lens
(FF) Floodplain fines occasional
SG Sediment gravity flows lobes or sheets
(CH) Channels few and small
GB Gravel bedforms tabular bodies
SG Sediment gravity flows lobes or sheets
P Sh St P Fmr P Gmm P Gp Gt P Gmm Gmg
4
0
Ephemeral mass-flow transport deposits (debris-flow) and poorly channelized coarse-bedload deposits. Superimposed calcrete developing. Proximal facies association in a poor channelized ephemeral alluvial fan system.
FA-5
CH Channels few and small
GB Gravel bedforms tabular bodies
FF Floodplain fines relatively extensive sheets few to several m thick
CH Channels few and small
SB Sandy bedforms sheets and channel-fill lens
GB Gravel bars and bedforms tabular bodies
P Gt P Fmr Sh St P Gp Gcm
4
0
Poorly channelized coarse to medium bedload transport deposits (ephemeral small channels). Superimposed calcretes and in general carbonate pedogenesis. Medial to proximal facies association in a poorly channelized ephemeral alluvial fan system.
FA-6
FF Floodplain fines extensive sheets (100´s m to km wide and 10´s m thick)
PC Pedogenic calcretes thin to thick (massive, laminar, brecciated) paleosol carbonate
(CH) Channels few and small
LS Laminated sand sheet unchannelized or poorly channelized
SB Sandy bedforms sheets and channel-fill lens
P Fmr P Fmr P St Sh
4
0
Periodically exposed flood-plain vertical accretion deposits and occasionally ephemeral poor channelized to no channelized medium bedload deposits. Superimposed calcretes and pedogenesis. Distal alluvial fan or fluvial flood-plains and peri-lacustrine palustrine facies association.
FA-7
CTB Carbonate tabular bodies extensive bodies of continental carbonates
PLC Palustrine carbonate
SLC Shallow lacustrine carbonate
MF Mixed floodplain peri-lacustrine muddy-carbonate palustrine floodplain
CTB Carbonate tabular bodies extensive bodies of continental carbonates
PLC Palustrine carbonate
SLC Shallow lacustrine carbonate
Ln Lm P Mr Ln Lm Lb
4
0
Carbonate sedimentation in shallow continental quiet waters and periodical subaerial exposure (palustrine). Superimposed pedogenesis. Shallow lacustrine to palustrine carbonate facies association.
LEGEND
Horizontal bedding
Planar cross-bedding
Trough cross-bedding
Lateral accretion
Calcrete
Root traces
Intraclasts
Black pebbles
Charophytes
Ostracods
Gastropods
Fragmented bioclasts
Carbonate nodules in mudstone
Carbonate nodules
Matrix-supported conglomerate
Clast-supported conglomerate
Coarse to fine sandstone
Sandy siliciclastic mudstone
Marl
Limestone

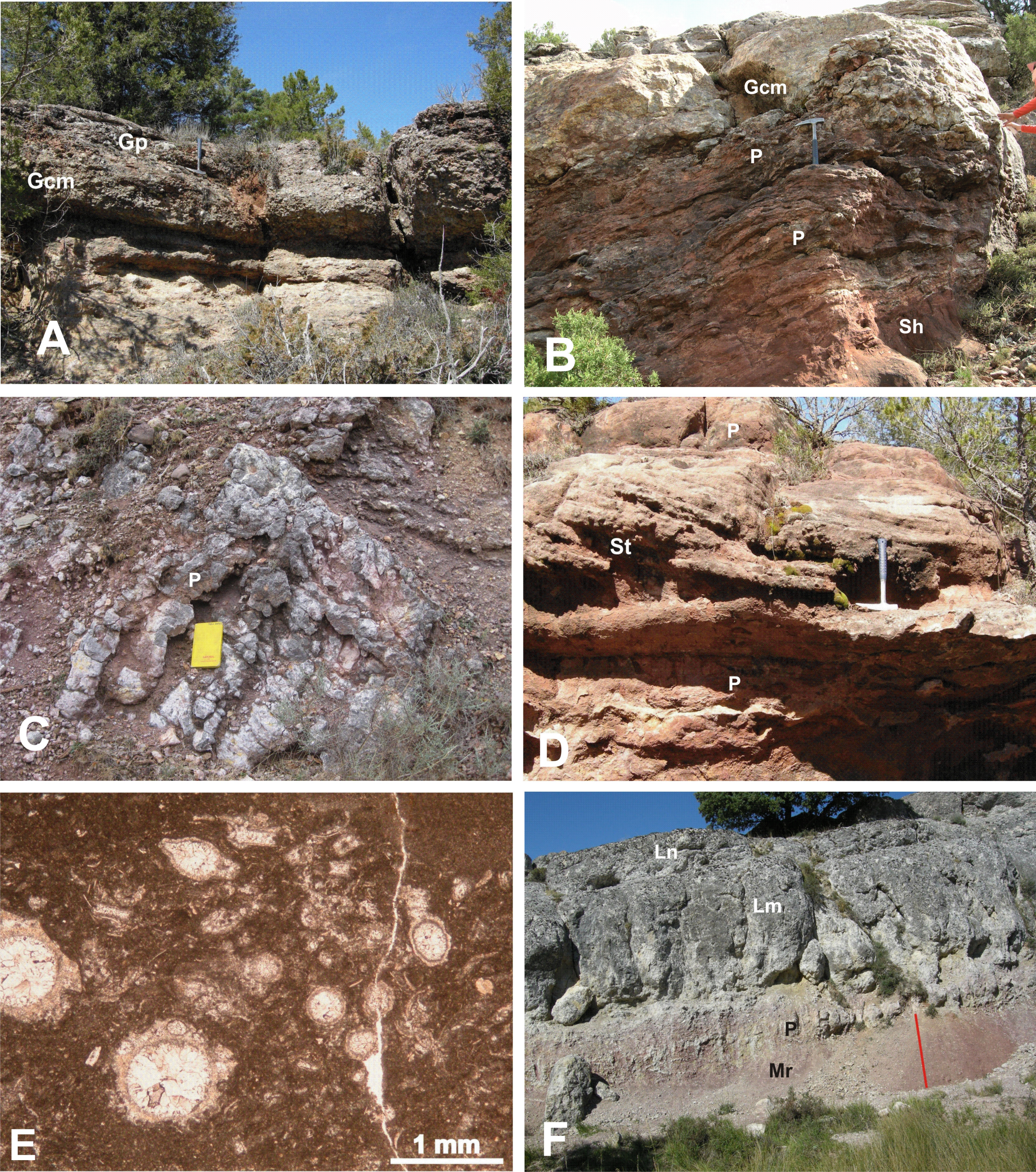

RUPELO(RU)
SG
GB
SB
FF
9%
11%
8%
72%
FA-4 = SG+GB
FA-5 = GB+SB+(FF)
SG GB SB LA FF
JARAMILLO QUEMADO(JQ)
SG
GB
SB
FF
5%
21%
3%
71%
FA-4 = SG+GB
FA-5 = GB+SB+(FF)
SG GB SB LA FF
VIZCAINOS ST1(VZ ST1)
SG
GB
SB
LA
FF
1%
23%
5%
12%
59%
FA-1 = SG+GB+SB
FA-2 = LA+FF
SG GB SB LA FF
VIZCAINOS ST2(VZ ST2)
GB
SB
FF
5%
25%
70%
FA-3 = GB+SB+(FF)
FA-2 = FF+(SB)
SG GB SB LA FF
TERRAZAS 2(TR 2)
GB
SB
FF
17%
13%
70%
FA-3 = GB+SB+(FF)
FA-2 = FF+(SB)
SG GB SB LA FF
ARROYO DEL HELECHAL(AHE)
SG
GB
SB
FF
25%
7%
20%
48%
FA-4 = SG+GB+SB
FA-6 = FF
SG GB SB LA FF
MAMOLAR N (MAN)
GB
SB
FF
11%
32%
57%
FA-5 = GB+SB
FA-6 = FF+SB
SG GB SB LA FF
BREZALES(BR)
GB
SB
FF
7%
8%
85%
FA-5 = GB+SB+(FF)
FA-6 = FF+(SB)
SG GB SB LA FF

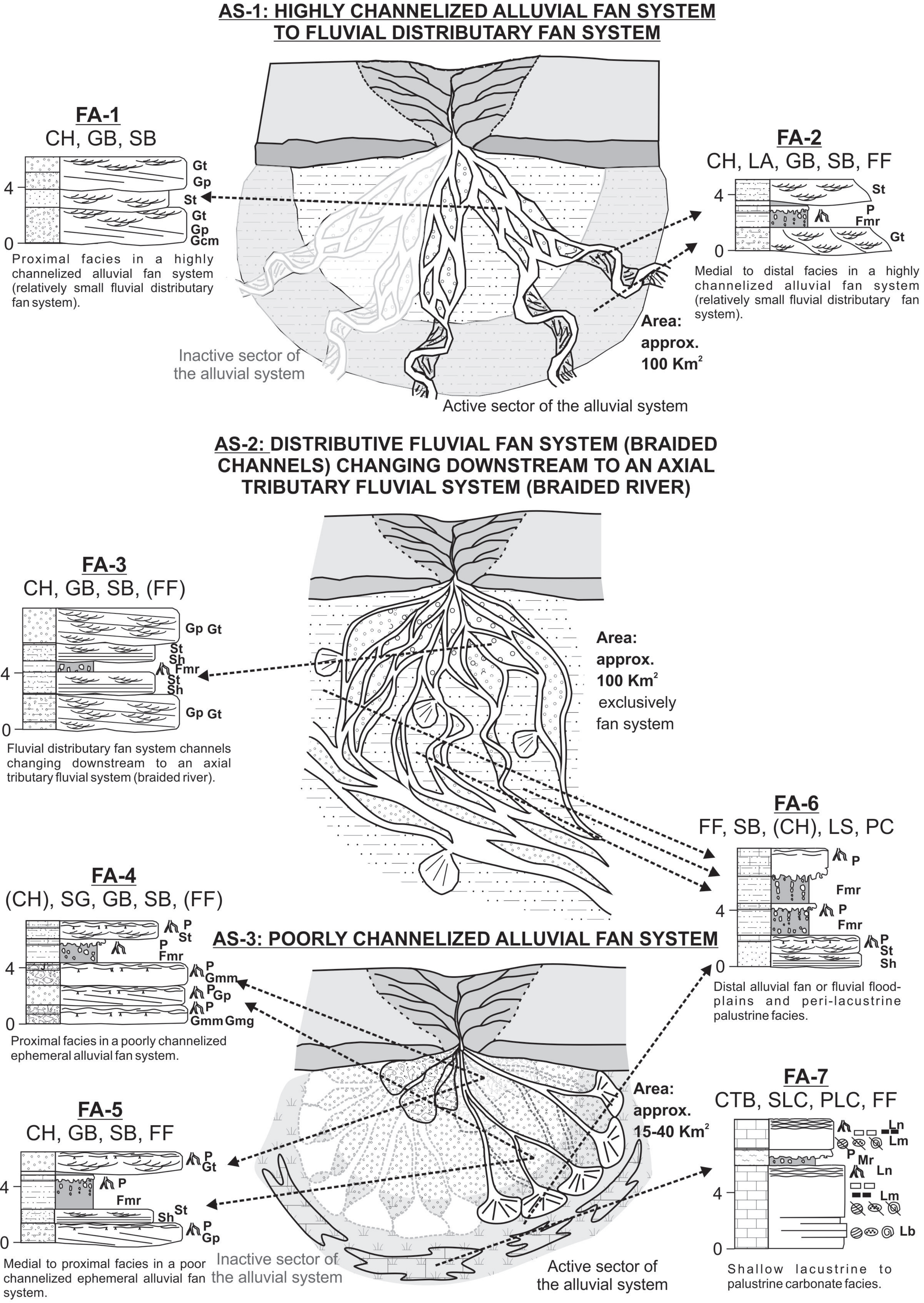


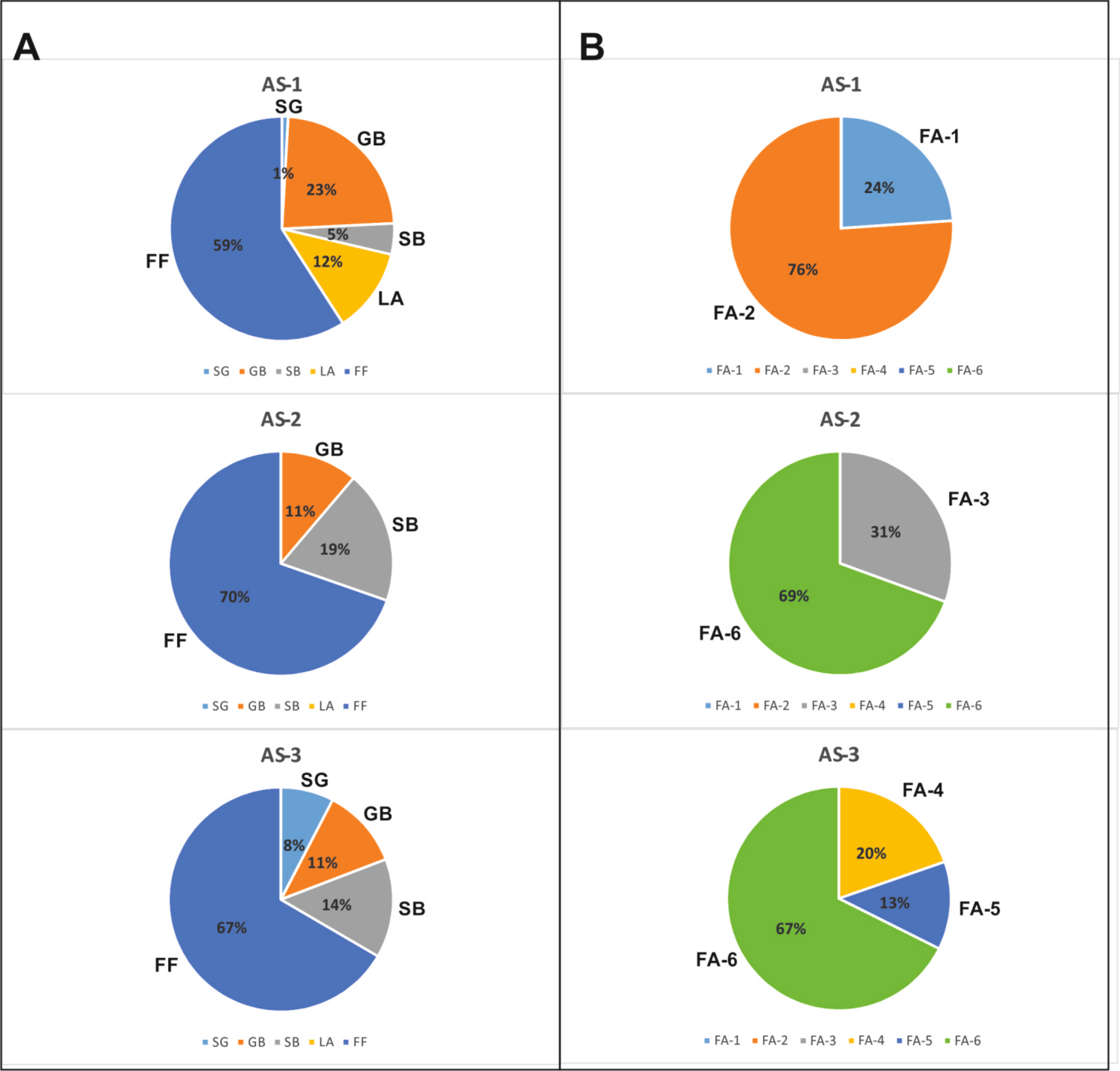
A
TO
PA
AC
MO
RU
A'
A''
B
CU
QU
CM
B'
B''
Quintanilla Halfgraben
Rupelo Halfgraben
2 km 2 km
20 m
NNE
C
JQ
PM
CTV
TR2 TR1
VZ
C'
C''
Jaramillo Halfgraben
Vizcainos Halfgraben
FACIES ASSOCIATIONS
FA-4
FA-3
FA-2
FA-1
FA-7
FA-6
FA-5
Facies change
Limit between Stage 1 and Stage 2
Upper and lower limit of DS1
Outcrops lacking DS1
AHE
E
E'
E''
F
F'
F''
CF
MAN
AR
D
D'
PI
GAS
BR
ES
Helechal Halfgraben
Mamolar Halfgraben
Huerta del Rey Halfgraben
Brezales Halfgraben
North Sector
Central Sector
South Sector
20 Km.



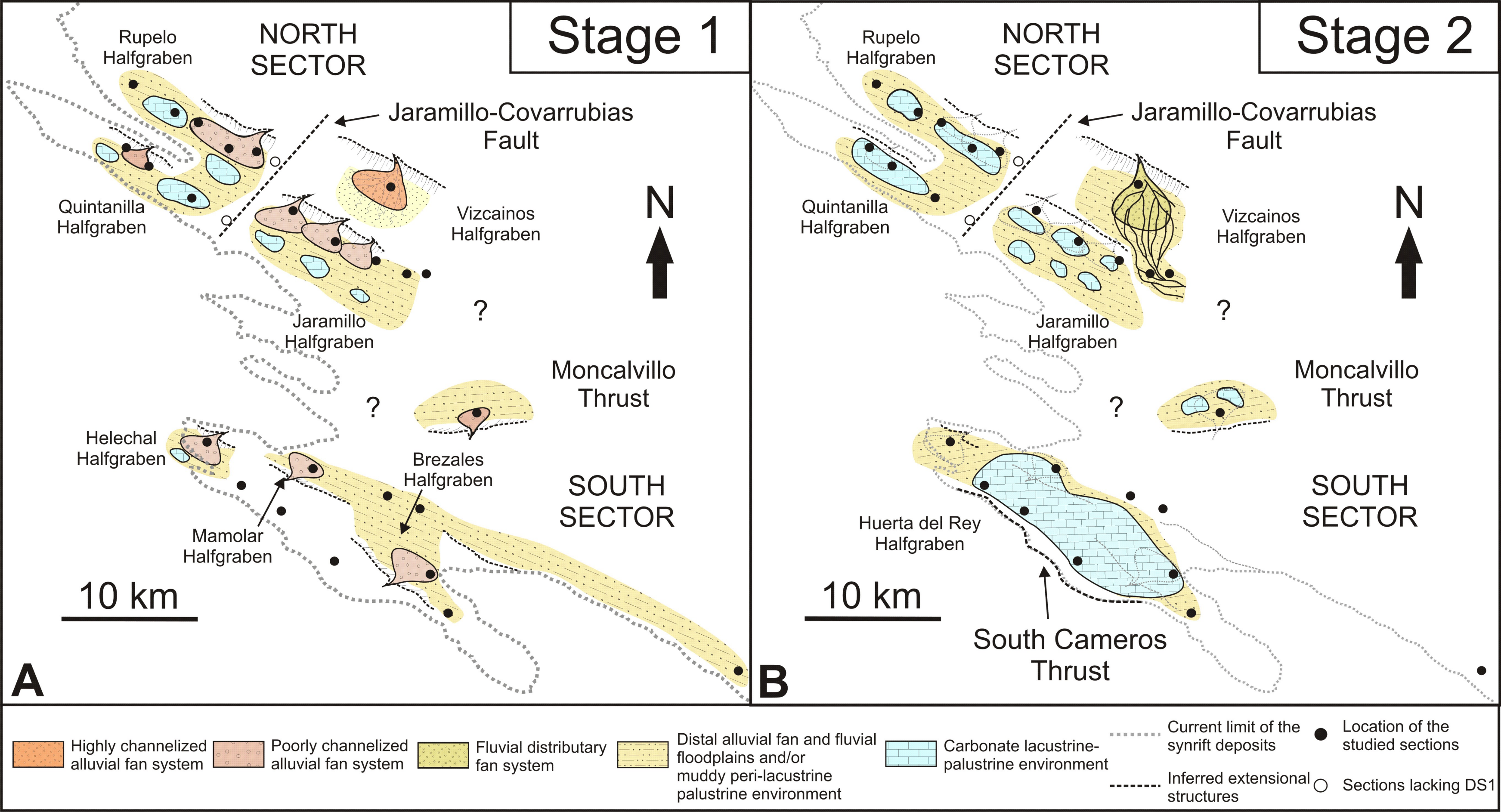
A
Gt
Gp
B
Gt
Fmr
C
Gp
Gt
Gt
D1
D2
E
Gmm
F
P
Gmm
Sh


Gp
Gcm
A
Gcm
P
P
Sh
B
P
C
P
St
P
D
1 mm
E
Ln
Lm
P
Mr
F


AS-1: HIGHLY CHANNELIZED ALLUVIAL FAN SYSTEM TO FLUVIAL DISTRIBUTARY FAN SYSTEM
FA-1
CH, GB, SB
Gt
Gp
St
Gt
Gp
Gcm
4
0
Proximal facies in a highly channelized alluvial fan system (relatively small fluvial distributary fan system).
FA-2
CH, LA, GB, SB, FF
St
P
Fmr
Gt
4
0
Medial to distal facies in a highly channelized alluvial fan system (relatively small fluvial distributary fan system).
Area: approx. 100 Km2
Inactive sector of the alluvial system
Active sector of the alluvial system
AS-2: DISTRIBUTIVE FLUVIAL FAN SYSTEM (BRAIDED CHANNELS) CHANGING DOWNSTREAM TO AN AXIAL TRIBUTARY FLUVIAL SYSTEM (BRAIDED RIVER)
FA-3
CH, GB, SB, (FF)
Gp Gt
St
Sh
Fmr
St
Sh
Gp Gt
4
0
Fluvial distributary fan system channels changing downstream to an axial tributary fluvial system (braided river).
Area: approx. 100 Km2 exclusively fan system
FA-6
FF, SB, (CH), LS, PC
P
Fmr
P
Fmr
P
St
Sh
4
0
Distal alluvial fan or fluvial flood-plains and peri-lacustrine palustrine facies.
FA-4
(CH), SG, GB, SB, (FF)
P
St
P
Fmr
P
Gmm
P
Gp
P
Gmm Gmg
4
0
Proximal facies in a poorly channelized ephemeral alluvial fan system.
AS-3: POORLY CHANNELIZED ALLUVIAL FAN SYSTEM
Area: approx. 15-40 Km2
FA-5
CH, GB, SB, FF
P
Gt
P
Fmr
Sh St
P
Gp
4
0
Medial to proximal facies in a poor channelized ephemeral alluvial fan system.
Inactive sector of the alluvial system
Active sector of the alluvial system
FA-7
CTB, SLC, PLC, FF
Ln
Lm
P
Mr
Ln
Lm
Lb
4
0
Shallow lacustrine to palustrine carbonate facies.



A
AS-1
SG
GB
1%
23%
5%
SB
59%
12%
FF
LA
SG GB SB LA FF
AS-2
GB
11%
SB
19%
70%
FF
SG GB SB LA FF
AS-3
SG
GB
8%
11%
14%
SB
67%
FF
SG GB SB LA FF
B
AS-1
FA-1
24%
76%
FA-2
FA-1 FA-2 FA-3 FA-4 FA-5 FA-6
AS-2
FA-3
31%
69%
FA-6
FA-1 FA-2 FA-3 FA-4 FA-5 FA-6
AS-3
FA-4
20%
13%
FA-5
67%
FA-6
FA-1 FA-2 FA-3 FA-4 FA-5 FA-6


Stage 1
Rupelo Halfgraben
NORTH SECTOR
Jaramillo-Covarrubias Fault
Quintanilla Halfgraben
Vizcainos Halfgraben
N
?
Jaramillo Halfgraben
Moncalvillo Thrust
?
Helechal Halfgraben
Brezales Halfgraben
SOUTH SECTOR
Mamolar Halfgraben
10 km
A
Stage 2
Rupelo Halfgraben
NORTH SECTOR
Jaramillo-Covarrubias Fault
Quintanilla Halfgraben
Vizcainos Halfgraben
N
?
Jaramillo Halfgraben
Moncalvillo Thrust
?
Huerta del Rey Halfgraben
SOUTH SECTOR
10 km
South Cameros Thrust
B
Highly channelized alluvial fan system
Poorly channelized alluvial fan system
Fluvial distributary fan system
Distal alluvial fan and fluvial floodplains and/or muddy peri-lacustrine palustrine environment
Carbonate lacustrine-palustrine environment
Current limit of the synrift deposits
Inferred extensional structures
Location of the studied sections
Sections lacking DS1